CRANFIELD UNIVERSITY

Kate Jackson

DEVELOPMENT OF A BAYESIAN NETWORK BASED HYBRID-DECISION SUPPORT PROCESS FOR POTABLE WATER MANAGEMENT IN THE CONTEXT OF THE WATER FRAMEWORK DIRECTIVE

School of Applied Sciences

Engineering Doctorate (EngD)
Academic Year 2012

Supervisors
Dr. Peter Howsam, Dr. David Parsons
Professor Paul Jeffrey

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This thesis is submitted in partial fulfilment of the requirements for the degree of EngD.

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Abstract

Uncertain and complex environmental legislation governing the management of water resources has presented significant challenges to those responsible for identifying investment options to manage potable water supplies. This study aimed to develop a decision support process to enable a UK water company to understand and characterise the complex and uncertain implications of the Water Framework Directive (WFD) on the management of potable water supply. A flexible, exploratory and participatory approach was adopted, and included a central reference group comprised of managers representing different departments within the water company. Semi-structured interviews, informal discussions, focus groups, field visits, water company data, academic and legislative documentation, as well as UK water sector literature and observations by the researcher provided data which informed the criteria for and the population of a new Bayesian Network (BN) based Hybrid-Decision Support Process (Hybrid-DSP). Using BNs as a basis for decision support allowed the integration of diverse variables, as well as identifying and representing the relationships between them. The visual representation that BNs provided of the interrelationships between the variables, facilitated organisational learning in relation to the implications of the WFD for potable water management, which led to clearer identification of potential organisational responses. This study demonstrates the practical implications for the use of BNs within a water company in the UK. Furthermore a new BN based Hybrid-DSP has been developed through this study, which offers a systematic and holistic template to identify and analyse water company responses to the implementation of environmental legislation.

Acknowledgements

The research has been a remarkable and life changing experience which challenged me in so many different and unexpected ways. The people I have come into contact with, places I have visited, and events I have been part of, have all contributed to an unforgettable life learning experience.

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Finally I express particular appreciation for the love and patience of my husband and his constant support through this challenging era of our lives. You have been an amazing source of strength, and always supported me throughout all the very demanding and difficult times I, and we, have faced. I cannot thank you enough. It is now our time to catch up on missed adventures and celebrate each and every day ahead of us!

Presentations

Jackson, K (2007) Presentation to Anglian Water Services: Reference Group meeting No.2, Huntingdon (11th January 2007)

Jackson, K (2008) Presentation to Anglian Water Services: Reference Group meeting No.3, Peterborough (12th February 2008)

Jackson, K (2008) Presentation to the Innovation Team in Anglian Water Services, Peterborough (29th February, 2008).

Jackson, K (2008) Presentation to the Anglian Water Services WFD Working Group, Huntingdon (3rd March 2008)

Jackson, K (2008) Presentation to Anglian Water Services: Reference Group meeting No.4, Peterborough (15th May 2008)

Jackson, K (2008) Presentation to Anglian Water Services: Reference Group meeting No.5, Huntingdon (13th August 2008)

Jackson, K (2008) Presentation to Anglian Water Services: Reference Group meeting No.6, Peterborough (19th December 2008)

Jackson, K (2009) Presentation to Anglian Water Services: Reference Group meeting No.7, Peterborough (23rd April 2009)

Jackson, K (2009) Presentation to Anglian Water Services: Reference Group meeting No.8, Peterborough (26th August 2009)

Jackson, K (2009) Presentation to the Anglian Water Services WFD Working Group, Huntingdon (13th March 2009).

Jackson, K (2009) *From Catchment into supply: Modelling the implications of the Water Framework Directive and future water treatment investment strategies,* The 3rd Development in Water Treatment and Supply Conference at Buxton, Derbyshire on 1-2nd June 2009.

Jackson, K (2009) Presentation to a focus group in Anglian Water, regarding integration of the decision support process within the investment planning process, Peterborough (3rd November 2009).

Jackson, K (2009) Presentation to a focus group with consultants and Anglian Water, regarding integration of the decision support process within the investment planning process, Peterborough (3rd November 2009).

Jackson, K (2010) Presentation to Anglian Water Services: Reference Group meeting No.9, Peterborough (6th January 2010).

Jackson, K (2010) Presentation to Anglian Water Innovation Control Group (ICG), Peterborough (26th April 2010).

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Notation

AM	Adaptive Management
AMP	Asset Management Plan
AMP4	Asset Management Plan period 2005 – 2010
AMP5	Asset Management Plan period 2010 - 2015
AMP6	Asset Management Plan period 2015 – 2020
AMP7	Asset Management Plan period 2020 – 2025
AMP8	Asset Management Plan period 2025 – 2030
AWB	Artificial Water Bodies
AWS	Anglian Water Services Ltd
Bn/ BN	Bayesian networks (aka Bayes nets)
BBN	Bayesian Belief Networks (aka Bayesian networks)
BDN	Bayesian Decision Network
CAMS	Catchment Abstraction Management Strategy
CAPEX	Capital Expenditure
CCW	Consumer Council for Water
CIG	Common Implementation Guidance
CPT	Conditional Probability Table
CRAGS	Contamination Risk Assessment for Groundwater sources
DBN	Dynamic Bayesian Network
Defra	Department for Environment, Food and Rural Affairs
DPF	Diffuse pollution forum
DPSIR	Driving Force, Pressures, States, Impact, Response
DrWPA	Drinking Water Protected Area
DSP	Decision Support Process
DSS	Decision Support System
DWD	Drinking Water Directive
DWI	Drinking Water Inspectorate
DWSP	Drinking Water Safety Plan
EA	Environment Agency
EC	European Commission

EDSS	Environmental Decision Support System
EEA	European Environment Agency
EEC	European Economic Community
EMO	Evolutionary Multi-objective Optimisation (algorithm)
ERA	Ecological Risk Assessment
EU	European Union
FG	Focus Group
FORWARD	FORecasting of WAter
GIS	Geographical Information System
GQA	General Quality Assessment
GQA_{Biol}	General Quality Assessment score for Biology
GW	Groundwater
GWD	Groundwater Directive
HMWB	Heavily Modified Water Bodies
HOST	Hydrology of Soil Types
Hybrid-DSP	Hybrid-Decision Support Process
ICM	Integrated Catchment Management
ICMS	Interactive Component Modelling System
ID	Influence Diagram
ID	Identify number (for informants)
IM	Informant meeting
IWRM	Integrated Water Resource Management
MCL	Maximum contaminant level
MEM	Macro-Ecological Model
MERIT	Management of the Environment and Resources using Integrated Techniques
NEP	National Environment Programme
NeWater	New approaches to adaptive water management under uncertainty.
NGO	Non-governmental organisation
NVZ	Nitrate Vulnerable Zone
O&M	Operation and maintenance
OOBN	Object Orientated Bayesian Network

Ofwat	Water Services Regulation Authority (Office for Water Services)
OPEX	Operational Expenditure
PESTEL	Political, economic, social, technological, environmental, legal
PIP	Participatory and Integrated Planning
PoMs	Programme of Measures
PR04	Periodic Review 2004: for AMP4 (2005 – 2010)
PR09	Periodic Review 2009: for AMP5 (2010 – 2015)
PR14	Periodic Review 2014: for AMP6 (2015 – 2020)
RBD	River Basin District
RBMP	River Basin Management Plan
RBMP1	River Basin Management Plan period 2009-2015
RBMP2	River Basin Management Plan period 2015-2021
RBMP3	River Basin Management Plan period 2021-2027
RG	Reference group
RO	Reverse osmosis
R&V	Risk and Value
SDS	Strategic Direction Statement
SPZ	Source Protection Zone
SW	Surface water
SWOT	Strengths, weaknesses, opportunities, threats
SWRA	Surface Water Risk Assessment
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research
VoI/ VOI	Value of Information
WFD	Water Framework Directive
WFD WG	Water Framework Directive Working Group
WHO	World Health Organisation
WPZ	Water Protection Zones
WRM	Water Resources Management
WTi	Working Together initiative
WTW	Water Treatment Works

1 Introduction

1.1 Overview

This chapter introduces the background to the research undertaken and specifies the aim, research objectives and research questions together with their justification. The remaining chapters are also introduced to provide an overview of the thesis content.

1.2 Water resource management and decision making

Decision makers faced with identifying sustainable solutions for the management of water resources are increasingly experiencing complex and uncertain challenges. These stem from the characteristics of a mobile physical resource, both temporally and spatially, which is directly dependent on the increasingly uncertain climate, and by nature, is not able to be bounded by social administrative areas. Hence, managing water resources requires both an understanding of the complex and uncertain physical environment together with the increasingly contentious social concerns of both the general population and industry. Balancing all the diverse interests of stakeholders whilst managing both the availability and quality of water resources is therefore a demanding and challenging task which decision makers have to respond to. Legislation is a driver which can support the sustainable management of water resources, through the promotion of specific water quality standards and objectives, in addition to specific management approaches. The inter-connectedness of water resources presents a further degree of complexity, which requires an overarching approach to the management of the 'whole system' of water. This is specifically highlighted when events or activities which occur 'upstream' have a direct effect on water and its use 'downstream'.

1.3 Water resource management in the UK

Water resources in the United Kingdom (UK) are managed by a range of organisations which include private water companies (in England and Wales), not for profit companies (Welsh Water), and public owned companies (Scottish Water and Northern Ireland Water) operating alongside several government agencies. There are 26 water companies altogether, 14 water companies, which specialise in the supply of potable (drinking) water, and 12 water and wastewater companies, which provide both potable water supplies and treat wastewater. These are located in specific geographically constrained regions throughout the UK (WaterUK, 2012) (Figure 1.1).

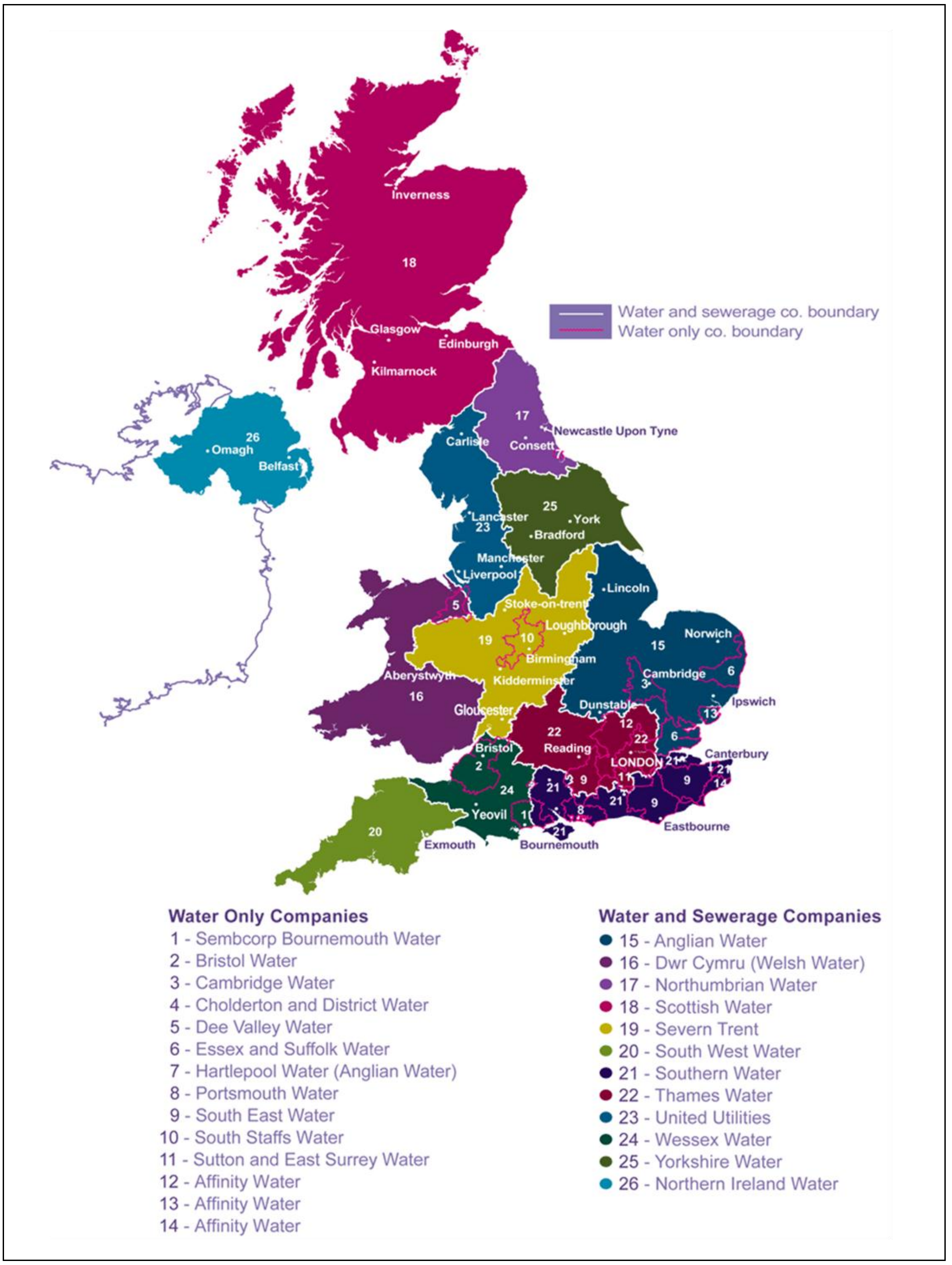


Figure 1.1: Map of UK water companies (Source: WaterUK, 2012)

The role of a water company includes the abstraction of water from surface and groundwater sources, followed by treatment of the water using a range of treatment technologies, so that the water can be supplied as potable water. The selection of treatment technology is dependent on the quality of the abstracted water, and the processes needed to achieve the standards for potable water. The relationship between water companies and the environment is therefore interdependent, with the availability and quality of water being subject, for example, to the prevailing climatic conditions, as well as the underlying geology, and land use. The prevailing climatic conditions present specific problems for water supply during periods of drought, as well as periods of flood, which have become increasingly frequent during recent decades (Defra, 2008). The impact of water company operations on the environment through the discharge of effluent from water and wastewater treatment processes, are also significant, for example, effluent high in nitrates can lead to impacts on the balance of the ecosystem in the receiving water body. The need to control the quantity of water abstracted and the quantity and quality of water released from water company operations requires close monitoring to ensure that water resources are sustainably managed.

Specific government agencies which have a regulatory role involve: the Drinking Water Inspectorate (DWI) who control drinking water quality, the Office for Water Services (Ofwat) who regulate water company asset management plans, and the Environment Agency (EA) who regulate the environmental implications of water company operations. These organisations in combination create tightly controlled operating conditions for UK water companies. Consequently, these strict operating conditions present a complex set of conditions to be satisfied in the determination of investment expenditure to ensure compliance with drinking water quality and environmental standards, as well as meeting customer expectations. To incorporate these multifaceted requirements for water resource management Asset Management Plans (AMPs) are prepared every five years which set out planned investment (AWS, 2009a). Recently these have been supplemented by 25 year Strategic Direction Statements (SDS) (AWS, 2007a), to aim to achieve longer-term planning horizons for water resource and infrastructure provision. This recent change towards a more long-term and sustainable approach to water management presents a step change to planning investments, which has been welcomed by the industry.

1.4 Environmental legislation and water resource management

The environmental legislation which governs the management of water resources has become increasingly complex over recent decades with a slew of European directives including: the Water Framework Directive (2000/60/EC), Marine Directive (2008/56/EC), Groundwater Directive (2006/118/EC), Nitrate Directive (91/676/EEC), and Pesticide Directive (2009/128/EC). This legislation has consequences for the way in which water resources are managed and may have conflicting or complementing implications. Understanding these legislative requirements and identifying appropriate organisational responses is now becoming a critical issue to ensure requirements are met and effective use of resources are made. The effectiveness of these decisions by an organisation, is dependent on the capability of an organisation to respond to the external operating environment. Therefore, knowledge and understanding of these changes is critical to identifying appropriate decisions and organisational strategies. The implementation of the EU Water Framework Directive (WFD) (2000/60/EC) requires an holistic approach to the management of water. This involves the rationalisation and updating of existing legislation and development of new Daughter Directives (e.g. Groundwater Directive [GWD]) and is focused on the development of the River Basin Planning concept. To achieve this, the WFD promotes the adoption of integrated and participatory approaches to decision making by decision makers. Organisations are now challenged in both understanding the specific details of the WFD and in identifying the implications and hence, the priorities for investment decisions to be made in response to the WFD.

The WFD requires overarching objectives (e.g. ‘good status’) to be met for specific water bodies and hence a refocus from previous specific water standards for water bodies. In this tradition, water companies had previously been concerned with delivering against specific targets for water quality control, with limited consideration for the wider water system. This change from specific targets to the overall ‘status’ of water bodies requires a much wider understanding of the management of the whole water system, and hence a change in the orientation and understanding of water companies regarding the effects of their operations. Thus, further engagement and awareness of other stakeholders activities in the use and management of water across the regions within which water companies operate is now required. This engagement is promoted through the WFD to actively share knowledge regarding the uses of water by other industries and the impacts of operations on water bodies. For example, additional monitoring of water bodies is now required, to understand how they are changing over time, and through this, build an evidence base from which further management decisions can be determined. Water companies need to actively understand how changes in both land use and water use ‘upstream’ of abstraction points may affect the use of water for potable water supply. This requires new understanding of the factors influencing the quality and availability of water resources to be used for potable water supplies. Central to this process is therefore a need to, engage with a wider range of stakeholders, in order to facilitate knowledge exchange and further develop organisational understanding of the factors influencing water quantity and quality. For wastewater, the newly identified objectives for water bodies receiving effluent from wastewater treatment facilities is likely to reduce the quantity of effluent that can be released and the concentrations of specific contaminants within that effluent. These restrictions may therefore require further investment in current or additional treatment processes and water companies now need to be better informed of the social and environmental contexts influencing the management of water bodies and catchments under their control.

Decision support techniques for water resource management have traditionally been focused on specific issues, targets or standards, which have historically been driven by physical and chemical water quality targets determined by legislation. The introduction of water ‘status’ objectives through the WFD presents a step change in the management of water bodies, requiring overall water quality and quantity objectives to be achieved. In achieving these objectives, holistic and integrated decisions including physical, chemical, biological and social aspects are to be made. Hence, further support in the water sector through the development of more holistic approaches to the strategic management of water resources is now required. Questions now being asked across the water sector include ‘How can integrated decisions be made with regard to water resource management?’ ‘How can multiple drivers be integrated within the decision making process?’ ‘How do we know what decision options to consider?’ Across Europe there has been an increase in the development of methods and approaches to address these such questions. One method in particular which has received recent attention is the use of Bayesian networks (BNs).

BNs have during the last decade been promoted as a technique to deliver integrated decision support to inform strategic governmental policies for water management. However, through a review of the BN literature (see Chapter 2) it is evident there have been limited applications of the technique for decision support within water companies. The perspectives of organisations on the use of such a technique is also not widely published within academic literature. Through the exploration of the use of BNs as a decision support process to inform water company potable water management strategies, additional knowledge can be engendered and contribute to the contemporary debate on their suitability for decision support in the water sector. A specific focus on the use of BNs as the basis of a Hybrid-Decision Support Process (DSP) would also inform the debate on the use of BNs combined with other decision support techniques. Therefore, this gap in literature has informed the subsequent research objectives presented in Section 1.5.

1.5 Research aim, objectives and research questions

The aim of this research is `*to support the water sector in developing integrative responses to environmental legislation through the design of a decision support process’*. To achieve this aim, research objectives (1 to 4), and research questions (1.1 to 4.1) were developed and are presented below, with the corresponding chapters in which they are addressed presented in Figure 1.2.

Objective 1: *Review the literature on decision support to understand decision support development, and review the suitability of Bayesian networks as a decision support method for the management of water resources.*

- RQ 1.1: How have BNs been used for decision support to inform strategies for water resources management?
- RQ 1.2: What is the perceived effectiveness of the use of BNs by end-users?

Objective 2: *Review existing organisational decision processes for potable water resource management within the case study organisation*.

- RQ 2.1: What existing decision tools and processes exist within the case study company for the management of water resources?
- RQ 2.2: How is environmental legislation (e.g. the WFD) incorporated into these tools and processes?

Objective 3: *Develop a decision support process to explore and assess the organisational implications of the Water Framework Directive on potable water management.*

- RQ 3.1: What are the criteria for the design of a decision support process to inform organisational responses to environmental legislation implementation?
- RQ 3.2: What methods are suitable for use as a decision support process?
- RQ 3.3: How should the methods be used?
- RQ 3.4: How should the decision support process be implemented within a case study organisation and what are the organisational requirements?

Objective 4: *Identify organisational responses to the decision support process*

- RQ 4.1: What are the organisational responses and perspectives to the design of a decision support process?

Research Objective 1 and associated Research Questions 1.1 and 1.2 were posed in response to the gap in the literature identified in Section 1.2. Research Objective 2 and associated Research Questions 2.1 and 2.2 were established as a result of the engagement with a UK water company (see Section 3.8). Here, a gap in knowledge became evident in relation to the incorporation of the WFD in investment decision making activities, which led to the formulation of Research Objective 3. This research objective is in response to the identified deficiency in the literature of an available decision support processes to identify and assess organisational implications of the WFD implementation for potable water management. In this research, BNs were proposed as the basis for the development of a Hybrid-DSP. Consequently Research Objective 4 further contributed towards the gap in the literature identified in Research Objective 1, by identifying organisational responses to the BN based Hybrid-DSP.

1.6 Research contribution

The main contributions to knowledge offered through this research are listed below:

1) **A new BN based Hybrid-Decision Support Process (DSP)** has been developed to support the assessment of the impact of environmental legislation on strategic organisational decisions in relation to the management of potable water.

2) **The gaining of extensive organisational responses from within a case study organisation on the use of a BN based Hybrid-DSP as a means to inform the management of potable water.** Organisational responses to the use of BNs were encouraging, indicating future applications of BNs for additional catchments, to understand the potential impact of environmental legislation on potable water management. However, concerns were highlighted by water managers regarding the site specific nature of BNs, as this could imply a high level of resource commitment to BNs, if applied across the whole region of an individual water treatment works (WTWs) and its catchments.

3) **The development of a process (Hybrid-DSP) that promotes organisational learning.** Using BNs as part of a participatory Hybrid-DSP facilitated organisational learning related to the integrated relationships between variables affecting the management of potable water. This led to the identification of potential management strategies for potable water, whilst also supporting the ethos of the WFD for participatory and integrated water management.

1.7 Thesis Structure

An overview of each chapter is provided below, with further illustration of the relationships between the research objectives and the thesis chapters in Figure 1.2.

Chapter 2: ***Decision support using Bayesian networks for water resource management: the UK water sector.***

The use of BN for water resources management is reviewed, and identifies a gap in knowledge for the application of BN in relation to organisational decision making in response to environmental legislation implementation within the UK water industry.

Chapter 3: ***Research approach and methods***

The research strategy and methods used to address the research questions is discussed with supporting rationale.

Chapter 4: ***Development of the Hybrid-DSP***

The requirements of the Hybrid-DSP are identified, together with the selection of techniques for incorporation into a new Hybrid-DSP. End-user observations and perspectives of the techniques are identified.

Chapter 5: ***Demonstration of the Hybrid-DSP***

The Hybrid-DSP is demonstrated and identifies generic and site specific organisational responses to the implementation of the WFD.

Chapter 6: ***Reflections and discussion***

A critical review of the output from the development and demonstration of the Hybrid-DSP and reflections on its use are discussed within the context of the reviewed literature.

Chapter 7: ***Conclusion, recommendations and further research***

A summary of the responses to the research questions is presented, along with a clear outline of the contribution to knowledge this study has provided. Limitations of the research are also identified, with recommendations for the Hybrid-DSP implementation and future research.

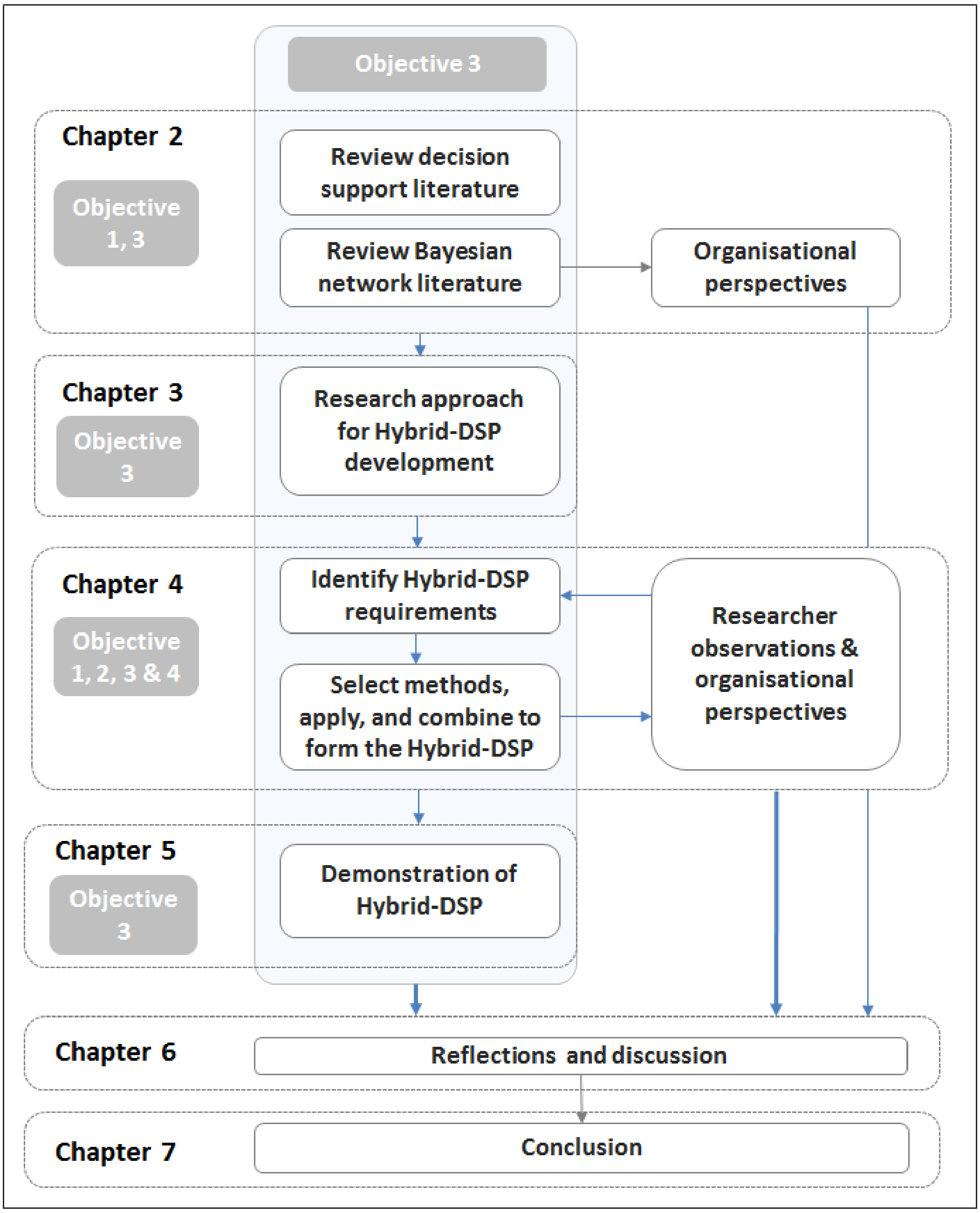


Figure 1.2: Overview of thesis structure

2 Decision support using Bayesian networks for water resource management: the UK water sector

2.1 Introduction

Decision support techniques for water resource management are commonly employed by water utilities. Bayesian networks (BNs), as a specific decision support technique, has recently received keen interest within the field of water management. This contemporary development has subsequently prompted a review and investigation into its deployment for water resources management, with specific reflection on its use in the UK. The findings from the review are discussed within this chapter in order to address Research Objective 1 (see Section 1.5). Of interest are the following investigative questions which have been asked of the literature, and inform the basis of the discussion in subsequent sections. “In what contexts have BNs been applied and what were the outcomes of their application?” (Section 2.4), “How has participation with stakeholders in the application of BNs been conducted and how useful has this been?” (Section 2.5.1), “How have dynamic Bayesian networks (DBNs) and object orientated Bayesian networks (OOBNs) been applied in water resources management and are these applications successful?” (Section 2.5.2), “In what way, and how effectively have BNs been coupled with other techniques?” (Section 2.5.3), “What are the benefits and challenges regarding the use of BNs for water resource management?” (Section 2.6), and “What organisational perspectives have been disclosed on the use of BNs in relation to water resources management?” (Section 2.7). Thus, in exploring these questions, a body of knowledge to which the outcome of this study contributes is established and is reflected in Figure 2.1.

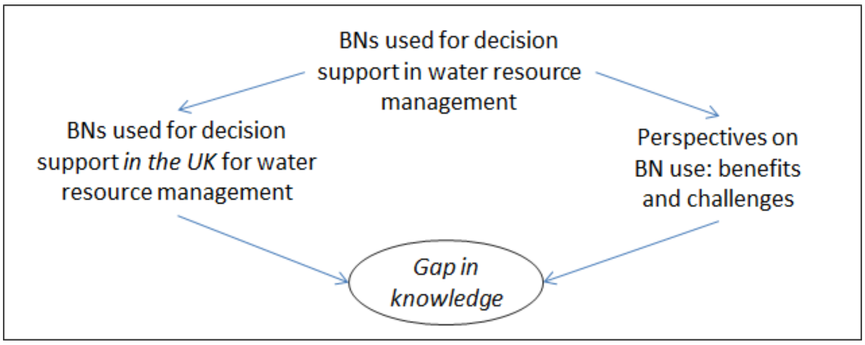


Figure 2.1: Area for knowledge contribution

2.2 Decision making and decision support

The development of methods and tools to support decisions over recent decades has become ever more complex, with changeable conditions in the problem domain becoming prevalent. These complex and uncertain conditions have a direct impact on the purpose of, and criteria for, decision support development (French and Geldermann, 2005). In the environmental sector, many diverse and trans-disciplinary factors (including physical, economic, environmental and social [Parker *et al.*, 2002]), as well as the various interrelating perspectives, interests and preferences of decision makers and stakeholders, present specific challenges for decision support (Jakeman *et al.*, 2008a). Understanding the requirements of an organisation and hence the design of decision support systems in this context, is particularly important (McIntosh *et al.*, 2008).

2.2.1 Decision support characteristics

Decision Support Systems (DSS) as defined by Finlay (1989), are systems containing ideas from several disciplines associated with information technology and decision analysis, which are used to improve the efficiency and effectiveness of managerial decision making. The purpose of DSS is to assist the decision maker in gaining an understanding of the problem domain (which is generally complex and ill-structured [Steiger, 1998]), and often involves using simplified models of reality (Turban *et al.*, 2007). DSS include among others, management information systems (MIS) (data retrieval systems, extrapolatory systems), and management intelligent systems (MINT) (preference determination systems, and scenario development systems) (Finlay, 1989). Turban *et al.* (2007) also identified the range of DSS to include tools for: visualisation, business analytics, strategy and performance management, communication and collaboration, knowledge management, and intelligent systems. Within the field of environmental and natural resource management there are many types of existing DSS as well as new decision support tools (DSTs) (Jakeman *et al.*, 2008a). Examples of existing DSTs include Decision and Information Support Tools (DIST) (McIntosh *et al.*, 2008), Environmental Decision Support Systems (EDSS) and Integrated Assessment (IA) (Rizzoli *et al.*, 2008; Merritt *et al.*, 2010); whilst developments in Environmental

Integrated Modelling Frameworks (EIMFs) are emerging to address the inherent complexities of EDSS and IA (Rizzoli *et al.*, 2008).

Each type of DST has individual features which make them suitable for different problem domains. For example, management intelligence systems (MINTS) can handle high levels of uncertainty, allow for increased expert judgement, and are able to be applied over a longer time frame; although would offer less detailed modelling of the system. Management information systems (MIS) however, require more certainty, less expert judgement, shorter time frame, and less interaction with the problem context (Finlay, 1989; Turban *et al.*, 2007). Within the variations of decision support for environmental applications, many are focused at the strategic level, and hence adopt features associated with MINTS (e.g. some EDSS and IEDSS systems [Merritt *et al.*, 2010]). The integration of different types of tool constitutes what are known as 'hybrid decision support tools' (Turban *et al.*, 2007), which is the term adopted within this research.

2.2.2 Decision support development

In designing decision support tools the type of control to be exercised by the decision maker (e.g. operational, managerial or strategic) and the decision making context (e.g. structured, semi-structured or unstructured decisions) have a direct influence on DSS design (Turban *et al.*, 2007). In addition, engaging the end-users and encouraging participation among stakeholders in decision support development is acknowledged by McIntosh *et al.* (2008) as a critical component in leading to successful decision support implementation and adoption. The development of the various decision support techniques can be simplified into the following sequence: (i) problem definition; (ii) constructing a model that describes the real world problem; and (iii) identifying and evaluating possible solutions to the problem (Turban *et al.*, 2007). The approach to decision support development adopted within this research uses these elements as a basis and is discussed in Section 3.4.3.

The approach to the development and implementation of various types of decision support requires an appreciation, from a business perspective, of the organisational context in which a particular DSS is to be used. This is in addition to the pertinent changes in the external business environment. To achieve this, a broad range of knowledge from different disciplines is required to guide the design and application of decision support. These include: decision analysis (Goodwin and Wright, 2004), information and knowledge engineering and computer science (Turban *et al.*, 2007), organisational behaviour (Hatch, 2006, Huczynski and Buchanan, 2007) strategic management (Johnson *et al.*, 2008) and strategic development of organisational capabilities (Stacey, 2003) as well as operational management (Slack *et al.*, 2007). Therefore, the use and design of decision support tools (DST) can be tailored to the specific business contexts in which they are deployed. The relationship between the pressures exerted by the business environment and the responses of an organisation are illustrated in Figure 2.2. These pressures can present opportunities for organisations to develop and thereby drive the requirements of DSS design to inform organisational decisions.

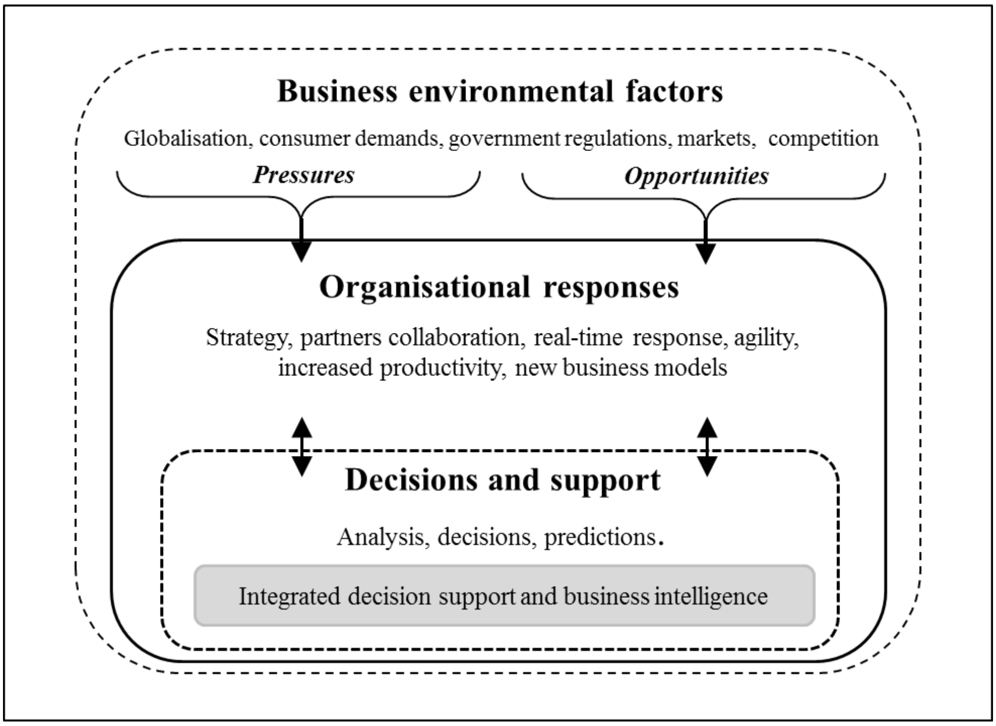


Figure 2.2: The business pressure-responses-support model (adapted from Turban *et al.*, 2007).

Some of the benefits of using decision support are listed by Turban *et al.* (2007:91) and include the ability to: ‘handle semi-structured and unstructured problems’, ‘provide support to managers at all levels including individuals and groups’ and ‘consider independent or sequential decisions’. Although decision support can be beneficial, there are some short-comings involved in the introduction of any new system or process within an organisation, specifically where the knowledge required to implement the new process may be beyond the existing capabilities of the organisation. Important features to consider in the development of decision support, which are drawn upon within this research (see Chapter 3 and 4) have been identified by McIntosh *et al.* (2008) as:

- Know the capabilities and limitations of DIST technologies
- Focus on the process not on the product
- Understand the roles, responsibilities and requirements of the decision support function
- Establish collaborative working relationships
- Build and maintain trust and credibility

Within the field of environmental and natural resource management decision support is becoming increasingly useful in helping professionals understand complex challenges. When predictive inadequacies in existing natural resource modelling have been experienced, further mechanistic data have traditionally been sought. However, these additional details will at some point exceed the ability of decision support tools to reduce model error adequately. To address this deficiency, probabilistic approaches to decision support could be used. Over the last decade one such approach: Bayesian networks (BNs), is now advocated as a technique for decision support suitable for application to multivariate decision problems. The remaining sections in this chapter review and explore the deployment of BNs within water resources management, and aim to inform the reader of the debate regarding their use as well as introducing the specific context in which the research has been undertaken. The implications for their inclusion as part of a Hybrid-DSP within this research is discussed within subsequent chapters.

2.3 Bayesian networks and decision support

Bayesian analysis originated from the work of the late Rev. Thomas Bayes (1701-1761), who first presented the formula for updating evidence based on subjective beliefs, known as Bayes Theorem (Formula 1) as a way of informing decisions. The probability, hence degree of belief, of A and B, $P(A)$ and $P(B)$ is conditionally dependent on the probability of A given B and B given A, hence $P(A|B)$ and $P(B|A)$.

$$P(B|A) = \frac{P(A|B)P(B)}{P(A)}$$

Formula 1: Bayes Theorem

The level of ignorance of human understanding is represented using Bayesian decision theory through a conceptual framework, which explicitly incorporates uncertainty related to information used to make a decision. Subjective beliefs can be used to inform and update BNs where limited data is available (Pearl, 1988; Jensen, 2001). The use of 'subjective Bayesian' approaches to inform decisions, as opposed to more commonly used 'frequentist'[1] approaches, continues to divide the field of decision analysis (Varis *et al.*, 2012). Although the debate is likely to continue, BNs are now recognised as both a valid modelling and decision support tool (Castelletti and Soncini-Sessa, 2007a).

The advantages of using BNs for decision support have been widely documented, with the primary beneficial features highlighted by Kjaerulff and Madsen (2008) as:

- the provision of coherent and mathematically sound handling of uncertainty
- normative decision making, automated construction and adaptation of models based on data
- intuitive and compact representation of cause-effect relations and (conditional) dependence and independence relations
- the provision of efficient solution of queries given evidence.

[1] Frequentist approach concerns the frequency of an event occurring within a number of repetitions of an experiment.

The ability to incorporate multiple sources of data and their application to multi-variate decision contexts, together with the incorporation of participation with stakeholders, are additional advantages of using BNs recognised by Cain *et al.* (1999). A detailed review of the specific benefits and challenges for water resource management is subsequently presented in Section 2.6.

2.3.1 Definition and features of BNs

The form of a BN is described by Jensen (2001) as consisting of; a set of variables and a set of directed edges between variables; where each variable has a finite set of mutually exclusive states, and collectively (both the variables and the directed edges) represent a directed acyclic graph (DAG) (Figure 2.3), with a conditional probability table being associated with each variable. Kjaerulff and Madsen (2008:8) add detail to this representation by stating that a BN is '*an acyclic directed graph (DAG) which defines a factorization of a joint probability distribution over the variables that are presented by the nodes of the DAG, where the factorisation is given by the directed links of the DAG*'.

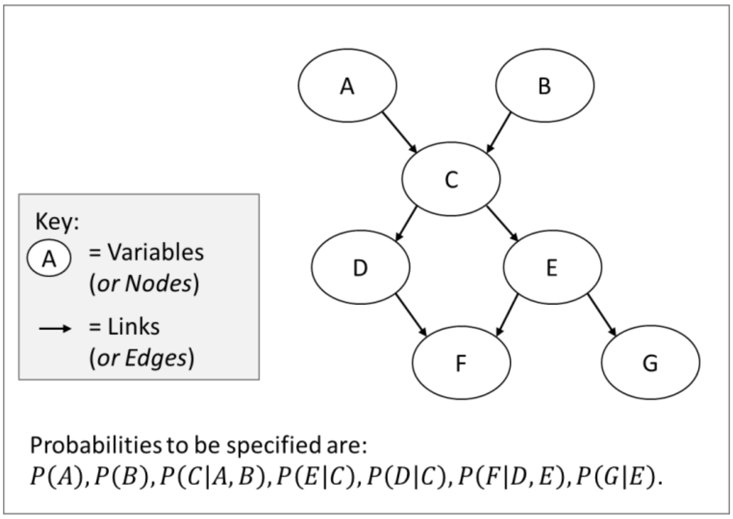


Figure 2.3: An example of a directed acyclic graph (DAG) (adapted from Jensen, 2001:20)

Specific variances in the application of BNs can lead to differences in the language being used. The type of node, the source of data used to populate the relationships and how the network is structured can impart subtle changes in terminology. Specific variances include Bayesian belief networks (BBNs) which utilise informed judgement and Bayesian decision networks (BDNs) or influence diagrams (IDs) which incorporate decision nodes and the utility of decision options (Pearl, 1988; Kjaerulff and Madsen, 2008). The structure of the BN can be further developed for large complex systems, where multiple copies of model components are incorporated within an Object-orientated Bayesian [or probabilistic] network (OOBN/ OOPN) (Kjaerulff and Madsen, 2008). Where components of the BN involve a time step, these BNs are termed Dynamic Bayesian Networks (DBNs). How these various forms of BNs have been applied to water resources is further discussed in Sections 2.4 and 2.5.

Formative steps in the construction of a BN include the identification of variables, the determination of the structure of the DAG, classification of variable states, and the population of the conditional probability tables which describe the relationships between the variables. Slight differences in terminology used with regard to the variables forming the BN structure, can engender confusion. For example Cain *et al.* (1999) categorise the variables as; 'implementing factors', 'interventions', 'intermediate factors', 'controlling factors', 'objectives and additional impacts'. Kjaerulff and Madsen (2008) however use 'background', 'problem', 'mediating' and 'symptom' variables. Generally the purpose of the variable classification is to establish a cause-effect relationship whilst also minimising the number of parent nodes to each child node, hence aiming to develop a relatively parsimonious BN structure. The representation of causal relationships within the BN can also be achieved through the use of algorithms which can be suitable within relatively new and contentious problem contexts (e.g. Alameddine *et al.*, 2011). Refinements in the construction of BNs are still developing and are directly dependent on; the purpose of the BNs in the first instance (e.g. as a social learning tool), the complexity of the problem domain, the methods used for BN application (e.g. involvement of stakeholders or not), the data type (e.g. qualitative or quantitative data), and the extent of data available (e.g. one off values, daily, monthly or yearly data sets).

BNs represent uncertainties in a model through the development of marginal probability distributions in parent nodes, which subsequently influence uncertainties in the child node states through the conditional probability distributions and cause-effect relationships. Forward and backward propagation of uncertainties can be used to determine either the effect of management decisions on the state of a variable of interest, or the effect on management decisions conditioned by the state of the output variable. Using Bayes Theorem, uncertainties are propagated as changes to the states of variables within the network, based on known and available evidence (Jensen, 2001; Kjaerulff and Madsen, 2008). The independence of the nodes within the DAG allow for conditional probabilities to be determined for each of the relationships between the nodes. The ability of BNs to model problem domains for which there may only be limited raw data available to quantify causal relationships is a clear advantage of the approach, as compared to other empirical, mechanistic or Markovian models, which require detailed knowledge of the internal processes and calibration of the data (Castelletti and Soncini-Sessa, 2007c).

Building on the causal relationships, the representation of scenarios within BNs provide a useful means to assess management intervention options. Sensitivity analysis also contributes to an understanding of the impact of changes in the background and problem variables on the output variables, which engenders more informed decisions. When undertaken in a collaborative way, a reduction in causal ambiguity and an increase in organisational strategic learning can be achieved (Ambrosini and Bowman, 2005). Increased knowledge regarding the causal relationships between variables can drive innovations, by focusing investments to address poorly understood causal relationships. Quentier (2007) also recognised that the use of BNs would lead to an increase in an organisation’s competitiveness, through the identification of technological and process resource investments, to flexibly manage organisational responses to changes in the business environment.

The key features of problem contexts in which BNs are a suitable analytical response have been identified by Kjaerulff and Madsen (2008) as requiring;

- well defined variables and events (i.e. values of the variables) of the problem domain,

- the availability of information about the causal relationships between variables and the conditional probabilities so that the relationships and utilities associated with decision options can be assessed,
- uncertainty in the relationship between some variables,
- the inclusion of decision making options within the problem domain, with a desire to maximise the utility of a decision.

These features are subsequently discussed in relation to BN applications within water resources management in Sections 2.4 and 2.5.

2.3.2 Contextual developments of BN applications

Applications of BNs have been previously limited by the computational power available for decision analytical applications, although in recent years this has been overcome, and a rapid increase in their use is emerging (Varis, 1997; Aguilera *et al.*, 2011). The increasing use has provided an impetus for related software development (Varis, 1997), as well as new algorithms and data pre-processing methods (e.g. Aguilera *et al.*, 2011). BNs are already recognised techniques associated with the fields of artificial intelligence and business intelligence support, with successful applications in the rail industry, insurance and operational risk management, air traffic management systems, as well as reliability predictions for military vehicles (Fenton and Neil, 2007). BNs to conduct policy analysis have been recognised previously to be a potentially useful technique (Granger Morgan and Henrion, 1990), although applications have only become more prevalent over the last decade; for example water policy development (Varis and Fraboulet-Jussila, 2002) and energy policy development (Cinar and Kayakutlu, 2010).

In the field of natural resource management (NRM) data are often scarce and the problem domain complex with interdependent economic, social, political, environmental and physical problems to address. The nature of the complicated and ambiguous challenges in NRM were recognised by Varis *et al.* (1994) as important components to be incorporated within the decisions taken. They were one of the first to recognise BNs as a suitable technique to handle these complex and uncertain features. Cain *et al.* (1999) also advocated their use, where they recognised BNs as providing "*a* *means by which comprehensive environmental plans can be developed dynamically so that they might realistically be expected to contribute to better management of natural resources*" (Cain *et al.*, 1999:132). Uusitalo (2007) further highlighted BNs as an increasingly popular technique in the field of environmental management and anticipated that BNs would become one of the standard methods used for the analysis of problems dominated by uncertainty in this field. Recent reviews have confirmed the continued interest in BNs as a decision technique, with applications to site specific management issues, through to whole river basin policy decisions (Barton *et al.*, 2012; Varis *et al.*, 2012).

Specifically in relation to water resources management, Olli Varis (Helsinki University of Technology, Finland), Kenneth H. Reckhow (Duke University, USA), Charles Batchelor and Jeremy Cain (Wallingford, UK), were among the first authors who considered BNs to be suitable for the modelling and management of surface water quality (Varis, 1997; Reckhow, 1999, Batchelor and Cain, 1999). Since these preliminary developments many research projects have been initiated, including recent developments resulting from the EU funded projects MERIT (2001-2004) and NeWater (2005-2009) (see Section 2.4). Applications have focused on testing BN methodology for modelling water quality and quantity issues, as well as integrating diverse scientific disciplines (e.g. economic, social, environmental) to inform water management strategies. The potential of BNs as a tool for analysing risks to drinking water through Water Safety Planning (WSP), has also been identified by Rosén *et al*. (2007) (although as yet limited applications have been made specifically for this purpose). These sustained developments and applications of BNs present a strong case for their continued development and application for water resource management. Within this chapter, 50 articles related to 24 case studies spanning the period 1993 – 2012 were reviewed based on their focus on water resources management (which included five articles concerned with two separate case study locations in the UK). Figure 2.4 illustrates the recent significant increase in publications since 2004 within this field.

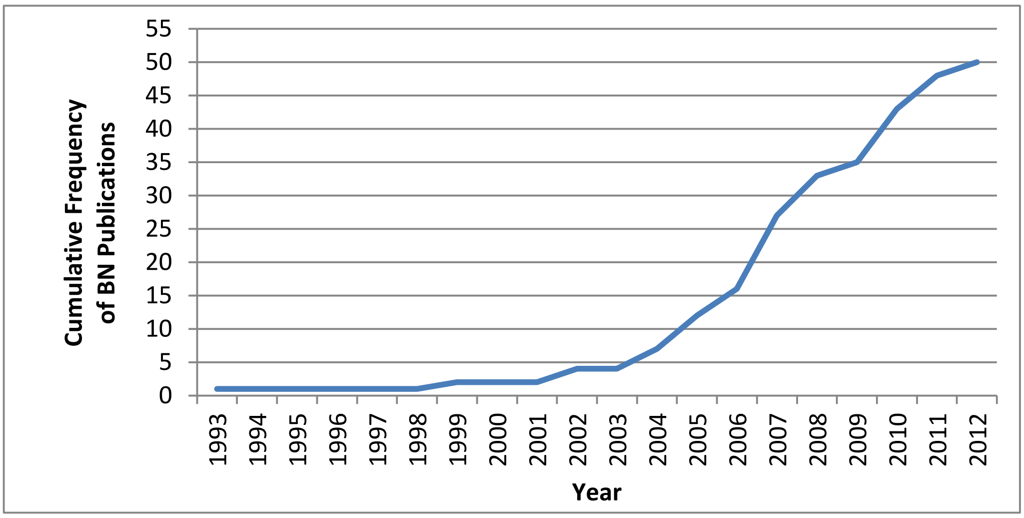


Figure 2.4: Water resource management BN publications between 1993-2012

The development of BN applications through these articles and case studies form the basis of the discussion presented within the subsequent sections of this chapter. Specific areas of interest include: the use of BNs as a participatory planning tool; their integration with other techniques; and perspectives on their use by participants and end-users. The case studies have been summarised and presented in Appendix A for reference.

2.4 BNs developments in water resource management

As stated in Chapter 1, the research is concerned with the development of integrative organisational responses to environmental legislation, which requires a review of strategic approaches for the development of such responses. In view of this, the use of BNs as a tool to understand and facilitate the implementation of environmental legislation is assessed and is discussed in Section 2.4.1. How BNs have been used for the management of water quality or quantity are also reviewed and discussed in Sections 2.4.3 and 2.4.4, with further discussion on their use in association with other techniques in Section 2.4.5 and specific applications within the UK in Section 2.4.6.

2.4.1 WFD implementation

BNs have recently been investigated as a potentially useful decision support technique, for use in response to the integrated and participatory management challenges for water resources, laid down through the implementation of the WFD. Two EU funded projects: the MERIT project (Management of the Environment and Resources using Integrated Techniques) between 2001-2004 and more recently the NeWater (New approaches to adaptive water management under uncertainty) project between 2005-2009 have contributed significantly to the development of BNs in this field.

The MERIT project aimed to investigate the use of BNs as a tool to facilitate participation in decision making in relation to the management of environmental resources. The project involved case studies in four countries (UK, Denmark, Italy, and Spain). Of these four, the Denmark case study represented one of the first applications of BNs to the problem of groundwater quality and implications for domestic water supply. In this case the focus on participatory engagement (see Section 2.5.1) with a water company was a significant success which led to greater understanding and awareness of the specific implications of the WFD for the management of groundwater quality (Henriksen *et al.*, 2004). Within Spain and the UK, the emphasis was on water demand management, which also involved a water company in the South East of the UK, and a water authority in Spain. The application of BNs within the Spanish case study has been very successful with further development of the use of BNs within the subsequent NeWater project. However, the application of BNs in the UK, only managed to demonstrate the potential of the technique as a strategic planning tool for water resource planning (Bromley *et al*., 2005). This study was limited as it was being conducted alongside an existing CAMS (Catchment Abstraction Management Strategy) process, which restricted the stakeholders engaged and limited the extent of decisions which could be made regarding the management of water demand. Following on from the MERIT project, the NeWater project used BNs as a technique to investigate the adoption of adaptive management (AM) to achieve integrated water resources management (IWRM) (NeWater, 2009a; NeWater, 2009b), using the initial work conducted through the MERIT project.

Both the MERIT and the NeWater projects were focused on the development of regional strategies for either the management of water quality (Denmark) or the management of water quantity (Spain, Italy, UK). Organisational strategies for managing water resources were not considered as part of these EU projects, instead the focus was on the development and assessment of regional water resource management. In addition further EU projects have supported research using BNs, specifically concerned with their use to assess the implications of the implementation of the WFD (Barton *et al.*, 2008). Recently Carmona *et al.* (2011b) concluded that the use of BNs meets the criteria set by the WFD to conduct integrated assessment, whilst also being able to promote active engagement by stakeholders in decision making, increasing public participation and developing social learning.

The outcome of using BNs in the Altiplano region (in Spain) indicated that even with WFD programmes of measures (PoMs) in place, the objective of good qualitative and quantitative status for groundwater would not be achievable by 2015, or even by 2024 with two additional time period extensions (Molina *et al.*, 2009). Hence, BNs in this case, highlighted the severity of the water management problem in the region and heightened the need for long-term commitment between stakeholders to seek a sustainable management approach to protect the use of water resources. BNs here, provided an integrated framework to assess the positive and negative consequences of WFD PoMs implementation, and hence the reality of intensive exploitation of groundwater resources amongst stakeholder groups (e.g. farmers, water authorities).

In the UK, the use of BNs as a technique for integrated catchment management (ICM) in response to the WFD has recently resulted in a new “integrated meta-model” known as the “Macro-Ecological Model” (MEM) (Holzkämper *et al.*, 2008; Kumar *et al.*, 2010). Incorporating BNs as part of the MEM, has been advantageous in integrating the objectives of the WFD for water quality (e.g. GQA_{Biol}), which could be assessed according to different management scenarios. Although the MEM provides a novel approach using BNs to inform integrated catchment management (ICM), the potential for the BN component to be applied to other catchments was questioned, due to the incorporation of catchment specific features. This constraint is further highlighted in Section 2.6.

2.4.2 Management of WTWs

The use of BNs to inform the management of potable water treatment works (WTW), concerned with water quality using SW have been applied in only three instances through work undertaken by Pike (2004); Ghabayen *et al*. (2004); Zhu and McBean, (2007). Pike (2004) undertook a unique surface water quality study modelling drinking water quality at the treatment level, to analyse when an exceedance of the maximum contaminant level (MCL) of specific parameters may occur. In this study, Pike, demonstrated the use of BNs as a decision support tool and acknowledged BNs as being beneficial in planning and policy making to understand why and where water quality problems may occur; and consequently how to prevent them. The study combined operator judgement on the cause-and-effect relationships between variables as well as data related to violations and hydrological conditions for different treatment systems. The application of BNs in this instance revealed qualitative relationships within the data which were unknown to the operator, and consequently improved the operators knowledge regarding WTW responses to changes in SW quality. However, both the degree of improvement in knowledge of the operator and the subjective judgements included in the BNs from the operator, were acknowledged to be dependent on the 'experience' of the operator. Pike (2004) highlighted that existing levels of experience of informants who contribute to BN construction should be recognised explicitly to understand the extent of existing knowledge and that gained through the use of BNs. In addition, the findings suggest that although BN applications for the management of WTW are possible, separate models would be required for each separate WTW system. This highlights a potential limiting factor, which would require further verification through additional case study applications. The study however was limited, due to only incorporating the perspective of one water operator. However, Pike (2004) also acknowledged that the inclusion of additional perspectives within a BN, through focus groups or consensus building activities would add to the generalizability of the model for water treatment violation management.

During the same period, another paper published by Ghabayen *et al.* (2004) also applied BNs to model a specific water treatment process: reverse osmosis (RO) for desalination. Both water quality (salinity) and water quantity (production volume) were incorporated as variables in the BN. In this application, BNs were argued to be useful to inform decision making for the optimisation of process management decisions including cost data, technical operational data and the physical properties of water quality. A minimum capital, and operational and maintenance (O&M) cost was identified, although through sensitivity analysis, the O&M cost was found to be strongly dependent on the energy consumption. Therefore, further investment in reducing the energy consumption of the RO process was recommended. It is also interesting to note, that the structure of the BN developed was concluded to be useful for any large scale RO process around the world (which contradicts the findings made by Pike, 2004), although this claim was not founded on further applications to other RO processes. The approach although demonstrated to be useful, was not discussed in relation to its applicability for water utilities, nor was the approach validated. Therefore, further validation of the proposed BN with other water utility stakeholders (hence decision makers) would be required, as well as additional applications of the proposed BN for RO to verify the extent of the generalisation of BNs application for WTW RO applications.

Conversely the selection of water treatment processes (instead of their optimisation as per Ghabayen, 2004 and Pike, 2004), in response to the water quality of sources used for potable supply has been conducted through an experimental demonstration of BNs by Zhu and McBean (2007). Here, BNs were used to model the expected raw water quality, and hence determine the selection of an appropriate WTW process to ensure potable water standards are maintained. Groups of nodes represented included: raw water quality, water processing alternatives, costs of water processing alternatives, quality of processed water, public health consequence of processed water, and utility of processed water. In this application, BNs were considered to be able to model in a decision-theoretic sense the variances in raw water quality and the implications for the process options (e.g. ozonation or disinfection) and their respective cost of use. Although the BN produced was intuitive and reflected water treatment options related to raw water quality, no practical demonstration to a case study was or has been conducted since. These three limited studies highlight the potential use of BNs to inform the management of water treatment processes, although also highlight the need for further research to fully explore the potential BNs could offer within this context.

2.4.3 Water quantity management

The deployment of BNs to address groundwater quantity issues focused primarily on the abstraction of water for either domestic use or for industrial application. In reviewing articles focused on BN applications for GW quantity management only 12 articles were identified, which all stemmed from the EU projects MERIT and NeWater. All 12 articles are concerned with case studies within Spain published between 2007 - 2011 (Carmona and Varela-Ortega, 2007; Carmona *et al.*, 2011a). The Mancha Occidental aquifer in Spain (both western and eastern regions), and more recently the Altiplano water system (Molina *et al.*, 2010; Molina *et al.*, 2011a) have been the case study locations for investigations into the use of BNs. These case studies all address the over exploitation of water resources with agricultural demands for irrigation water being the dominant pressure. The demands by agricultural users and the sustainability of the groundwater resource to support the agricultural economy is the central issue under assessment through the use of the BNs. In recent studies involving the use of BNs, in this context, Carmona *et al.* (2011a) identified both high offer price for the purchase of water rights coupled with strict enforcement of water restrictions on farmers by the River Basin Authority would be required to achieve even partial recovery of the aquifer water levels. Hence long-term water and land-use management strategies are recognised to be a high priority in order to manage future implications for water demand from GW sources. Through these studies, the ability of BNs to integrate multiple diverse variables within one decision framework was effectively demonstrated (e.g. physical variables – cropping patterns/ water availability; political variables – agricultural policy; economic variables – farm income [Carmona *et al.*, 2011b]). These studies indicate the increasing trend of the suitability of BNs for GW quantity management, the studies are limited to the experiences with Spain, hence further applications would need to be conducted to understand their use within other cultural and contextual settings influencing the management of GW quantity.

The management of surface water quantity using BNs has received even less attention with only five case studies (two in the UK) reported in the literature. Two of these studies were focused on the use of BNs coupled with other methods to model the impact of management decisions regarding Lake Maggiore (Italy/ Switzerland border) (Castelletti and Soncini-Sessa, 2007b) and the Vomano Water System in Italy (Castelletti and Soncini-Sessa, 2007c). The Vomano case study represented one of the first studies to address a more complex BN incorporating multiple disciplines, such as the costs of water management, coupled with environmental criteria, and the production of water supply for both domestic use and industrial power generation. The BNs in both these studies were able to be used for the components of the system being modelled for which information was poor or unavailable. This was also the case for BNs applied to model the institutional governance of water supply by Saravanan (2008). In this case the variables included within the BN included socio-cultural, institutional and ecological factors affecting participatory irrigation management in India. Within the UK only two case studies have demonstrated the application of BNs to surface water quantity issues, although this area of study has continued to develop in recent years (see Section 2.4.6) (Bromley *et al.*, 2005; Kumar *et al.*, 2010). These successful applications of BN within these studies indicates promising use for decision support, additional investigations into their use within additional case studies is required to establish in more detail the extent of their application. Specifically, research is required where BNs could be used to inform potable water supply and demand strategies.

The representation of the combination of surface and groundwater quantity management within the same BN has only been partially achieved in only two case studies. Martin de Santa Olalla (2005) presents the application of BNs to the study of sustainable abstraction from the aquifer unit in East Mancha in Spain. BNs were used to assess abstraction management options which included the restriction on the water available for irrigation and increased investment in building surface water infrastructure (Martin de Santa Olalla, 2005; Martin de Santa Olalla, 2007). The study's objective was to balance the economic costs of the change in irrigation and crop patterns for the farming sector, whilst predicting the likely recharge of the aquifer given further investment in surface water infrastructure. Another study similar to Martin de Santa Olalla *et al.* (2005) has recently been conducted by Asadilour *et al.* (2012) where five surface water dams and groundwater sources are combined to assess the implications for potable water supply to Tehran, in Iran. The scenarios for water management options, identified that increased water resources are required to avoid over exploitation of groundwater sources when supplying Tehran city, and consequently provided an evidence base to support future water management decisions for Tehran. These two studies demonstrate the potential for both surface water (SW) and groundwater (GW) to be combined in relation to modelling water quantity, although they also highlights the limited extent of application in linking these water bodies. The complexities of integrating the different GW and SW behaviours with regard to temporal and spatial distributions may be limiting factors for further applications. Further research into the relationships of these entities, and their representation within BNs is still required to establish the viability and limitations of BN applications in these contexts.

2.4.4 Water quality management

The use of BNs to assess the impact on potable water supply of GW contamination, has been demonstrated through a case study in Denmark and one in the Sultanate of Oman. The most prominent case study is the Havelse Wellfield in North Zealand, Copenhagen in Denmark (Henriksen *et al.*, 2004). This study focuses on pesticide contamination of groundwater supplies which supply Copenhagen city with an emphasis on participatory and integrated decision making for water management as driven by the WFD (Henriksen *et al.*, 2007d). Within this case study three main management actions were incorporated to address pesticide contamination in GW: voluntary farming contracts, afforestation and establishment of wetlands (Henriksen *et al.*, 2004). Further analysis on the cost-effectiveness of the different pesticide management plans has also subsequently been conducted (Henriksen *et al.*, 2007a). The use of BNs, especially during a participatory approach (see Section 2.5.1), engendered greater awareness and understanding of the factors influencing the management of GW resources, by both the water company and the local farmers. This case study represented a land mark development in the use of BNs, demonstrating the application of BNs to the assessment of management interventions affecting groundwater quality used for potable water supply. In comparison a separate study in the Sultanate of Oman, which included groundwater quality and the impact on water supply management for a city, was conducted by Shihab and Chalabi (2007). This study was instigated to develop techniques which would provide a better estimate of the stochastic variance attributed to the contamination of GW. Shihab and Chalabi (2007) constructed a BN to represent the probabilistic dependencies between water quality parameters (total dissolved solids, pH and electrical conductivity). In this case, BNs represented a novel attempt to assess groundwater quality contamination through understanding the inter-dependencies between the chemical characteristics of water quality. Although no direct impacts on decisions or management policies for GW were referred to, the study highlights the ability of BNs to focus on only physical or chemical parameters without necessarily incorporating social factors.

It is evident from the literature reviewed, that the application of BNs to groundwater quality management is still a new area of research. Issues of data availability and knowledge regarding the behaviour and movement of contaminants within groundwater sources is still largely unknown. Therefore within this context, characterised by paucity of information, the use of BNs, where expert judgement can be exercised, offers a potentially appealing approach to be considered by regional policy makers and water companies to inform GW management. Although at present this is still an emerging area, and further applications of BNs for GW quality management are required to increase the acceptability of the approach.

BNs have been used to address SW quality at both the catchment level and specifically for abstraction and water treatment. The particular challenges which prompt the application of BNs in this context include: social impacts of human activities on ecosystem services, such as the recreational use of surface waters, as well as physical issues concerning the availability of water for supply, and the impact of water quality on water treatment requirements. Water quality parameters used in these studies have included biological (e.g. chlorophyll concentration) and chemical (e.g. phosphorous and nitrogen concentration) determinands. Applications which incorporate a more integrated approach across knowledge boundaries (e.g. economic, social) have also been demonstrated (see Ticehurst *et al.*, 2007).

At a catchment level SW quality studies have focused on the representation of multiple stakeholder interests in the development of policy options for water management. A study involving the coastal lakes in New South Wales, Australia (Ticehurst *et al.,* 2007), successfully used BNs to understand the integrated management requirements (social and environmental) to achieve sustainable management of the coastal lakes. In a separate study of a lake in Norway, an economic assessment of the application of WFD measures to control phosphorous contamination was demonstrated using BNs (Barton *et al.*, 2005). In this instance, the use of BNs identified that further evidence is required to justify the proposed abatement measures to control phosphate concentrations in the lake. In addition Barton *et al*. (2005) also highlighted that the initial BN produced, required improvements to the resolution of the variable states to represent greater sensitivity within the BN to the implementation of the measures. This aspect of BN construction and its implications for BN use are further highlighted in Section 2.6.

Within the UK specifically, no published research has been identified which reports the application of BNs to ground or surface water quality management, either to inform policy level decisions or to inform operational or organisational decisions. The review of the water quality applications presented above also highlights that no studies have been conducted which incorporate both GW and SW quality parameters within a BN. This further highlights an area for BN development (e.g. where potable water sources are mixed from both surface water and groundwater sources).

In the review of the applications of BNs for the management of SW and GW quality, it is evident that multiple geographic scales can be accommodated. However it is apparent that more attention has been focused at the catchment scale of BN applications as compared to site specific WTW applications. Therefore, further studies are needed to explore the suitability of BNs to a wider range of case study contexts and to identify the extent of their applicability.

2.4.5 Water quality and quantity/ GW and SW combinations

During the review of the literature, articles which have achieved the more complex combination of GW and SW, or water quality and quantity, or aspects of both, were very limited. The most prominent combination was water quality and quantity in surface water case studies with six case studies spanning between 1999-2006. The combination of GW and SW in a BN has been achieved for only two case studies in 2005 and 2012, and only one case study has been reported for the combination of all four components of GW, SW, water quality and quantity (Chan *et al*., 2008).

Reckhow (1999) was one of the early authors to illustrate the application of BNs for modelling water quality and quantity. His work looked at nitrogen contamination of surface waters and combined the impact of water quantity related to stream flow impacting on the nitrogen concentration. Varis and Lahtela (2002) applied BNs to the wider region of the Senegal River, as an extension to the work conducted by Varis and Fraboulet-Jussila (2002) on the Lac de Guiers. In this study they integrated socio-economic impacts and environmental impacts in relation to river valley policies and development objectives, which were considered over a 10 year period. This study represented a complex application of BNs which incorporated 45 variables with 840 links. Although complex, BNs were demonstrated in this study to be useful in combining the many different aspects of the management of the Senegal River and illustrate the causal relationships between actions and impacts on the system, hence being able to assess the implications of different management options. A more specific study concerning phosphorous management within the East Canyon Creek was conducted by Ames *et al.* (2005). Here, Ames *et al*. used BNs in novel way to incorporate both water quality and quantity variables, including decision options for the management of phosphorous to assess environmental, social and economic implications of management actions. Varis and Keskinin (2006) used BNs as a policy analysis tool to assess the development options related to economic, environmental sustainability and poverty reduction goals using IWRM within the Tonle Sap Lake in Cambodia. More recently, Chan *et al.* (2010) have offered a detailed application of BNs to the case study of the Soloman Islands. In this study, catchment activities by indigenous people and activities used to manage water resources were combined to inform a catchment level integrated approach to water resource management. Chan *et al.* (2010) confirmed through this study the applicability of the use of BNs within developing countries where data and information may be scarce.

The flexibility of the use of BNs to the different contexts of water resource management has been demonstrated through the cases introduced in this section. Interestingly most applications of BNs within the water sector have been targeted at the catchment level, where focus has been on the integrated management of water resources at the policy level. These have been driven by IWRM agendas stimulated by the WFD and sustainability goals. Limited application of BNs have been targeted specifically at the abstraction of water or indeed the treatment of water for potable supply.

2.4.6 UK water sector and BN developments

During the last two decades, there has been very limited literature on the use of BNs within the water sector in the UK, with only five articles identified, four of which appeared in the last two years. These include an initial journal paper by Bromley *et al.* (2005), and more recently three conference papers (Kumar *et al.*, 2010; Shaw *et al.*, 2010; Gill *et al.*, 2010) with a subsequent journal article from Holzkämper *et al.* (2012). These articles varied with regard to the purpose of BN use. Although they were all applied to inform the strategic management of the water resource, only Bromley *et al.* (2005) and Shaw *et al.* (2010) applied BNs as a method independently of other methods. Kumar *et al.* (2010) and Holzkämper *et al.* (2012), applied BNs as part of a new method (Macro-Ecological Model [MEM]), as well as Gill *et al.* (2010) who incorporated three dimensional landscape visualisation with BNs.

The first paper on the use of BNs for the management of water resources in the UK was published by Bromley *et al* in 2005. The manuscript reported the application of a BN concerning the management of domestic water demand. This paper is of specific interest to this research, as it is the only paper which addresses BN applications incorporating a water company within the UK in the development of a BN. No discussion was made regarding the acceptability of the BN approach by the water industry regulators in this paper. Further assessment of the acceptability by regulators of the BN technique would be required if BN were to be fully implemented as a tool to manage water resources within the UK. Through this study, the use of BNs as a participatory tool (as per the purpose of the case study instigated through the MERIT project) was demonstrated to be successful within the UK for water resource management.

The contributions made by Kumar *et al.* (2010) and Holzkämper *et al.* (2012), to the debate on the use of BNs for water management focused on the issues of integrated catchment management concerned with urban drainage, flooding issues and arable land management. This was as part of an Environment Agency funded project to develop a new Macro-Ecological Model (MEM). Contributions from Shaw *et al.* (2010) and Gill *et al.* (2010) focused on the integration of catchment management activities concerned with the design of weirs along a stretch of the river Don. Of specific interest was the incorporation of the social implications of the design of the weirs and how they may affect the use of the river, as perceived by canoeists, hence clearly demonstrating the ability to use BNs in a participatory way to engage stakeholders in decision making (see Section 2.5.1).

The use of Bayesian inference (as opposed to Bayesian networks specifically) is not new to the UK water industry. Previous studies have used Bayesian inference approaches to study: the management of assets (Papathomas and Hocking, 2003), model the management of sewer maintenance activities (Fenner and Sweeting, 1999; Fenner *et al.*, 2000), and to manage underground assets (Freeman *et al.*, 1996). In addition, the use of Bayesian inference to analyse environmental data sets has also recently been reviewed by the UK Environment Agency, and is now identified as a useful technique for informing the classification of water bodies through river basin monitoring programmes (Ellis and Wyatt, 2009). However, although these examples illustrate the development of the use of Bayesian approaches within asset management, they do not explicitly report the use of a Bayesian network (i.e. a DAG see Section 2.3.1). Bayesian approaches to support decision making, are now becoming more widely recognised and subsequently represent an area of further research for the use of BNs specifically within the UK water sector.

2.5 Methodological approaches for BN applications

In the previous section, the contextual trends and developments of BNs were discussed. This section reviews the approaches used to apply BNs within these contexts in relation to the use of participation, structural developments (e.g. DBN, OOBN), and the application and coupling of additional methods and techniques with BNs. Although guidelines for the application of BN have been produced (e.g. Cain, 1999; Bromley, 2005; Marcot *et al.*, 2006) each application is different and is dependent on a range of factors. These include: the purpose of BNs use, the context in which they are used, the types of variables to be included, the availability of data, the organisations and stakeholders involved (and the capabilities of the participants), and the time and financial resources available.

2.5.1 Participation and BNs

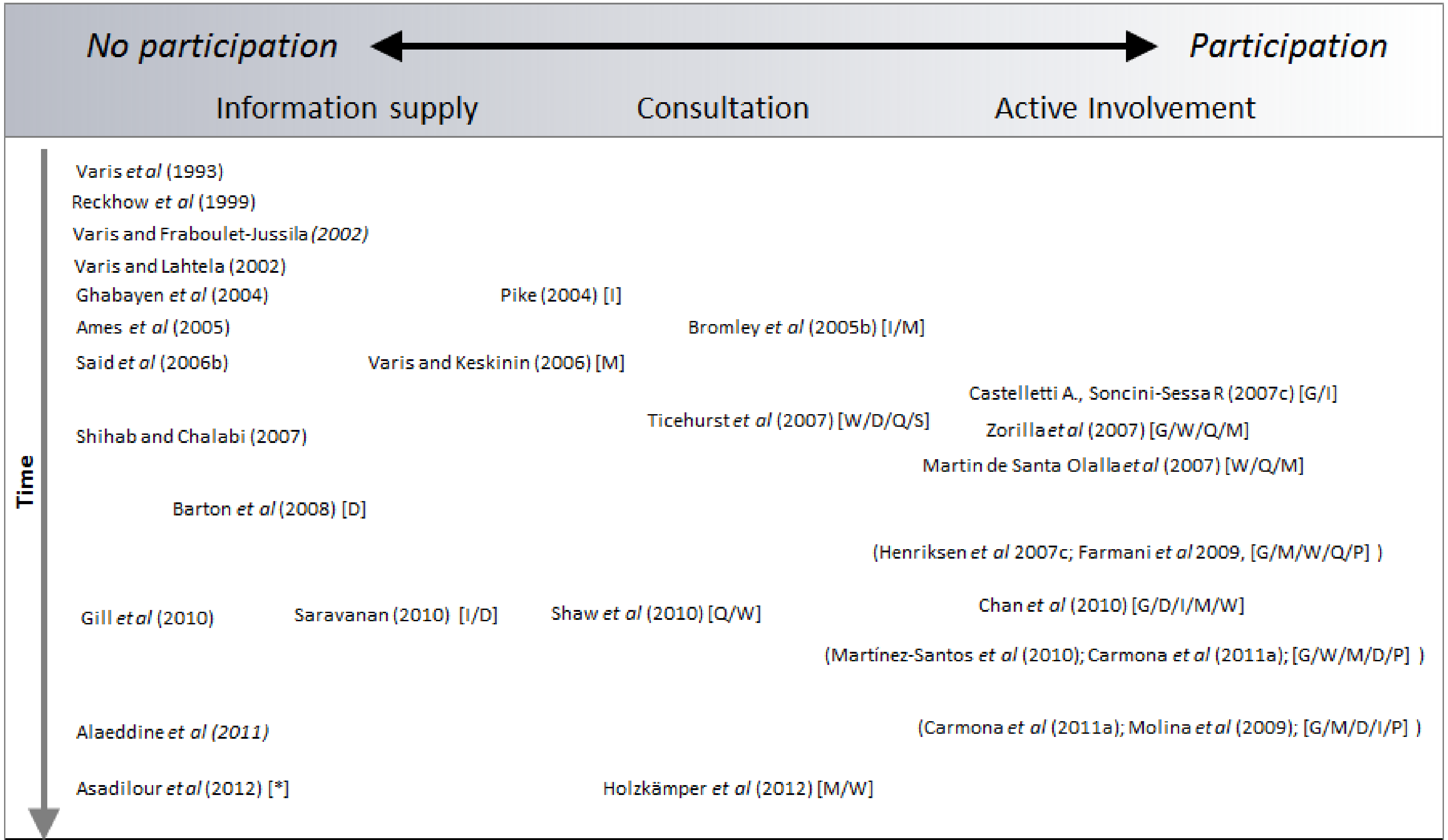
Participation in the construction of BNs has not been used in all cases. Cain (2001) initially developed guidelines for BN applications with more recent development by Bromley (2005) as a result of the MERIT project. The early studies by Cain *et al.* (1999) and Cain *et al.* (2003) regarded participative decision making in NRM as being influential in determining the success of natural resource management plan development. This was purported to be achieved through the development of an understanding of the management problem and generation of ownership of the plan by the stakeholders involved. Further guidelines for stakeholder engagement were developed from the subsequent MERIT project which identified specific objectives for the purpose of engagement (Bromley, 2005:22). These include:

- To identify people's concerns and interests
- To resolve conflicting interests

- To gather local information and information based on practical experience
- To test expert knowledge
- To increase the transparency of the BN development process
- To enhance social learning
- To reach a consensus view on the most appropriate BN for the decision process.

There are no orthodox methods by which engagement can be conducted (Bromley, 2005), and as such various methods have been applied. To include participation in BN construction, the development of a stakeholder engagement plan is recommended by Bromley (2005) to document a common understanding of the issues and concerns as well as specific goals and objectives to be achieved. The studies conducted through the MERIT (Henriksen *et al.*, 2007c) and NeWater projects (Henriksen *et al.*, 2007b) initially acknowledged and further promoted the benefits of BNs as a participatory technique. More recently, Farmani *et al.* (2009:305) identified that active stakeholder engagement used in the construction of BNs was a difficult process, where the researcher (who may also act as a facilitator) has to guide the group in the construction of a BN, as well as in the identification of probabilities to be used in the BN.

Case studies with active involvement include: the MERIT and NeWater case studies (Loddon Catchment, UK; Vomano Water System; Western Mancha Occidental aquifer, Spain; Western Mancha Occidental aquifer, Spain; Havelse Wellfield catchment, Denmark; Mancha Occidental aquifer, Spain; Altiplano Water system, Spain), as well as a recent case study in the Hongulia Catchment, Soloman Islands. All these applications were concerned with informing policies for the management of water resources. In contrast BN applications with no participation have had a range of purposes including; initial applications to test the suitability of the technique (e.g. Varis *et al*., 1993; Reckhow *et al*., 1999), optimisation of WTW processes (Ghabayen *et al*., 2004), development of algorithms to determine BN structures (e.g. Alameddine *et al*. 2011), whilst also trialled for the assessment of policy options for river basin management (e.g. Varis and Lahtela, 2002). Although BN applications without participation have been conducted, greater emphasis on the use of the technique as a participatory tool has been the focus in recent years (Figure 2.5).



Note: CS = Case study, [D] = Discussions, [G] = Stakeholder group, [I] = Interviews, [M] = Meetings, [Q] = Questionnaires, [W] = Workshop, [P] = publications/media coverage, [S] software for end-users, [*] = not clear. The scale between participation and none participation is graded coarsely with the EC (2003) [CIS No.8] participatory guidance scale of information supply, consultation and active involvement.

Figure 2.5: Spectrum of participation in BN construction and application

The types and extent of participation illustrated in Figure 2.5, indicate the breadth of engagement methods which have been used in the recent MERIT and NeWater studies actively encouraging engagement. These participatory approaches included workshops, questionnaires, interviews, meetings, media coverage, software development and general discussions. The extent of the success of the techniques are discussed in the following paragraphs.

Factors which determine the extent and success of stakeholder participation relate to; the stakeholders ability to understand and accept the BN methodology, the stakeholders knowledge of the problem domain and their willingness to engage in the BN construction process (e.g. in the provision of data including subjective views for CPTs), as well as the stakeholders ability to reach agreement on the problem domain to be modelled using BNs. In the latter case issues such as the purpose of the BN, the context of the problem domain, the types of variables involved, should be agreed for BNs to be constructed. The additional overarching constraint includes the provision of time and resources available (e.g. finances, data, people) to work with and populate BNs. The extent of the impact of these factors on BN applications are different for every BN due to the local physical and political conditions and cultures. Within the Loddon case study in the UK, the unfamiliarity of BNs with stakeholders presented an initial problem, due to the stakeholders greater familiarity with deterministic models for water management. However, through the use of an illustration of the BN approach, stakeholders were able to understand the technique and engage more productively in the development of a BN for water demand management (Bromley *et al*., 2005).

Interestingly within the Denmark case study a "leading committee" was established which had experience in project leadership and stakeholder participation, although it was acknowledged they had limited experience of BNs prior to the start of the project. This committee ensured detailed processes were in place to engage with stakeholders throughout the use of BNs to inform GW management decisions. Public meetings were a successful approach, as part of the process which promoted engagement and identified stakeholders to be represented on a local citizen group (Farmani *et al*., 2009). The success of active stakeholder engagement in this case, was also attributed to the existing culture of the involvement of stakeholders in decision making within the country (Bromley, 2005).

The importance of using independent facilitators was recognised during the application of BNs in Demark, to ensure the facilitators remained neutral and not engaged as either an end-user or project manager for the project (Farmani *et al.*, 2009). In addition clear rules of participatory engagement are required to be set, in order for BNs to be developed (Henriksen *et al.*, 2007c). Individual meetings with informants were also found in this case, to be more beneficial to obtain details to support BN development, rather than groups in excess of five members, which instead became a political positioning environment. Data was successfully obtained to populate the CPTs via focused meetings with specific stakeholders who had a greater understanding of the nature of specific relationships between variables (Henriksen *et al.*, 2007c).

The way in which professional groups and local citizen groups, within the Denmark case study, organised themselves and contributed to the BN development process informed development of the research strategy used here. Two separate groups were set up with their respective stakeholders (one professional group, one citizen group) to explore and understand the problem context and identify variables for BN construction. The citizens group seemed to be dominated by local politics, and ultimately, it opposed the work being conducted on the exploration of protection measures for groundwater supplies. The professional group also had political interests, although in this case this involved political positioning of stakeholder organisational interests. Therefore one to one meetings were used with specific organisations, to side-step the political issues, and focus on identifying specific issues to be incorporated in the BN design.

Within the Western Mancha case study in Spain, collaboration with stakeholder groups had already started before the use of BNs had been introduced, therefore the success of stakeholder engagement was enhanced by the willingness of stakeholders across this catchment to actively engage in further development work using BNs (Zorrilla *et al.*, 2007). Martínez-Santos *et al.* (2010) ensured the roles and responsibilities of stakeholders involved in the development of BNs were made clear, which helped to ensure commitment and involvement in the construction of BNs. In addition, the importance of identifying policies for the long-term management of water resources in Spain, was also recognised through the substantial financial backing provided by the Spanish government (US$ 7500 million) to investigate methods which could be used. The intensive use of BNs in this case study location has delivered many publications which report the successful application of BNs as both a tool to inform policy options, whilst also to facilitate engagement with stakeholders with an interest and influence in the management of water resources in Spain. The use of BNs has also been received positively by the Spanish authorities, where its use has promoted greater participation in decision making and exploring water resource management options, which has been a significant achievement for an area in which participation was not previously supported (Martínez-Santos *et al.*, 2010).

The use of large research teams with individual representatives for different subject areas was a common theme in the NeWater and MERIT projects. This provided a greater level of knowledge on the properties of groundwater and the influential drivers affecting its management (Martinez-Santos *et al.*, 2010; Farmani *et al.*, 2009). Henriksen *et al*. (2007c) also postulated that BNs have great value because they require a negotiation process which promoted interactive dialogue. However, Castelletti and Soncini-Sessa (2007b) do not agree, arguing instead that BNs do not facilitate the incorporation of multiple perspectives, and hence are only useful for “what if” analysis to evaluate alternative actions. Although, BNs have been reported to successfully incorporate alternative perspectives in many cases, Castelletti and Soncini-Sessa (2007b) suggest that other methods, such as influence diagrams, may offer alternative approaches that more clearly represent the specific individual perspectives used in the BNs. However, the use of such methods is problematic when dynamic representations of problem domains are required, and therefore Castelletti and Soncini-Sessa (2007b) identify the need for further exploration of alternative methods that can specifically incorporate individual perspectives (e.g. mathematical programming or optimal control methods).

A wide range of stakeholders have been represented in the various case studies previously discussed. Examples include farmers, herdsmen and fishermen (Varis and Lahtela, 2002); farmers, irrigation organisations, domestic and industrial water users (Martin de Santa Olalla, 2005), water companies (Bromley *et al.*, 2005; Henriksen *et al.*, 2007a; Martínez-Santos *et al.*, 2010) customary land owners, government and water management agencies, and non-government agencies (NGOs) (Chan *et al.*, 2010). This illustrates the flexibility of the technique in its use with a wide range of stakeholders. However, the extent of stakeholder participation in the construction of BNs has varied, with stakeholders in some cases being directly involved in the design of BNs, whilst in other cases, they have only been provide with information to populate the BN.

Although the purpose and benefits of public participation in BN construction have been outlined previously by (Bromley, 2005:22), the factors limiting the involvement of public participation in the construction of BNs has also been noted by Henriksen *et al*. (2007c) to include:

- a lack of resources (time, money, staff),
- a lack of rules of participation,
- a lack of in-depth involvement of authorities,
- a lack of hands-on use of BNs for the stakeholders,
- and a lack of professional supervision of the process.

Similar issues were identified to varying degrees within the other case studies reviewed.

2.5.2 Structural developments

A limitation of standard BNs is the inability to include feedback cycles (Barton *et al.*, 2008). One method by which feedback cycles can be incorporated is through the use of a time-sliced approach to the structure of the network (Kjaerulff and Madsen, 2008). This allows for the consequences of a decision in one period to be followed through into a subsequent time period. Initial papers published using BNs, assumed a one year time frame to consider the impact of the decision interventions made (e.g. Martin de Santa Olalla *et al.*, 2005). However many early papers did not explicitly address the temporal scale of the problem context. Initial developments in dynamic Bayesian networks

(DBN) have now been demonstrated by Barton *et al.* (2005) and Shihab and Chalabi (2007) to surface and groundwater quality contexts respectfully. Currently no applications of DBN to water quantity issues for GW or SW have been reported in the literature. The use of DBN is still controversial, due to the recognised limitations of BN software to incorporate dynamic features, with increasing model complexity through the use of time steps being the main issue. Instead many applications are conducted on a fixed timescale or with short timescales (e.g. a year). However, the use of time steps can also support strategic decisions over the longer-term for the management of catchments (e.g. Varis and Fraboulet-Jussila, 2002). Although these recent publications highlight the potential for DBNs, the limited number of publications also suggests further research is required to verify the suitability of DBN for use informing decisions regarding water management.

The use of modular BNs has been reported by Kumar *et al.* (2008) as an up and coming area for further research. In Barton *et al.* (2005) and Barton *et al.* (2008) BNs were applied to model abatement measures for surface water management. Time steps were incorporated with "measures" before the WFD and after WFD implementation, as well as the incorporation of an OOBN function. This allowed for repetitive sub model components to represent the environmental state of a lake, and the cost effectiveness of WFD measure implementation over successive time periods. Barton *et al.* (2008) identified that keeping the model simple for the use of OOBN is crucial, due to each OOBN being related to each time period of interest. This was also observed in a more recent application to the Altiplano water system in Spain. Here, Molina *et al.* (2010) developed an OOBN in an innovative study to model four separate aquifer water systems, integrating economic, hydrological and social factors. This study, therefore demonstrated a practical method of constructing OOBN to simulate water management actions across the region. In this case, a one year time period was used, although the authors recognised that further time slices could be incorporated to highlight the impact of management interventions over time.

Where OOBN are being developed, the importance of stakeholder collaboration in the validation process has been recognised as critical to ensure the models developed are credible, and that stakeholders agree with the representation of the problem domain (Barton *et al*., 2008; Molina *et al.*, 2011a). Although BN model validation is a generic issue, it becomes more important as the complexity of the model increases.

One of the advantages of using OOBN as demonstrated by Carmona *et al.* (2011b) within the Upper Guadiana basin in Spain, is the inclusion of repetitive structures of different farm types within the same model at different scales which can be analysed simultaneously. The impact of management measures at the catchment level on the separate farm types could therefore be aggregated using common variables to understand how management measures would simultaneously affect farm income and the aquifer at different scales. Although within this paper, the impact of the measures on the different geographic scales were accounted for, how the impacts of the management measures accumulated over multiple time periods was not represented. Through these studies, the use of OOBN is now recognised to be a new area for research within water resources management which has been further endorsed by Carmona *et al.* (2011a).

2.5.3 Coupling of methods and techniques with BNs

BNs can be used as either decision support systems (DSS) in their own right, through the use of decision and utility nodes, or as part of a more complex DSS where BNs are coupled with other techniques (Castelletti and Soncini-Sessa, 2007b). The coupling of a range of methods and techniques to support BN applications has been an expanding area. This has been due to increasing use of BNs by industry and academia. Methods have been combined to collect and pre-process data to inform variables within the BNs or to link with other software systems for specific decision support requirements. The types of concatenation have been recognised by Kumar *et al.* (2010) as either “hard” coupling through software, or “soft” coupling focused on participatory techniques. These advances illustrate the flexibility of BNs as a tool which can be integrated with other techniques and methods to serve different purposes. In response to these developments, BNs are now becoming referred to as `meta-modelling` frameworks (e.g. Barton *et al.*, 2008; Holzkämper *et al.*, 2012).

Problem domains can be identified and structured manually through the use of data and expert opinion using manual classification of variables and relationships (e.g. Kjaerulff and Madsen, 2008), or through the use of algorithms (e.g. Alameddine *et al.*, 2011) to automate structured learning as is facilitated for example within the BN software Hugin A/S Expert. The use of such automated structured learning requires data sets for variables which are then used to determine the relationships between the variables. However, when large data sets are limited, expert opinion is used to inform the structure. Techniques to assist experts to inform the structure of a BN include, among others, systems approaches, casual frameworks, and conceptual diagrams to establish causal relationships between variables.

In the case study by Saravanan (2008, 2010) a systems approach was used to understand a problem domain concerned with the analysis of institutions governing water resources. Chan *et al.* (2008) and Chan *et al.* (2010) also used a systems framework for the establishment of the linkages between variables across spatial, temporal and governance scales. The study by Barton *et al.* (2008) incorporated the use of the DPSI (R) framework (Smeets and Weterings, 1999) to identify variables concerned with WFD developments and the integrated assessment of land use options combined with the costs to achieve lake status objectives. The limitation of BNs to incorporate acyclic graph structures, prevented Barton *et al.* from including `Responses` as a category of variables within the BN. Langmead *et al.* (2009) also utilised the DPSIR framework to identify variables and inform the conceptual models of socio-economic drivers affecting the marine ecosystem. However only the D, P and S components were utilised within the BN model to quantify the causal relationships and assess alternative management options. These developments in the use of DPSIR combined with BNs represent initial attempts to integrate problem identification and structuring techniques to further enhance the use of BNs.

Carmona *et al.* (2007) proposed the application of BNs coupled with an agro-economic model as a decision support system, which was further developed using participation with stakeholders (Carmona *et al.*, 2011a; Carmona *et al.*, 2011b). The coupling of the methods successfully provided a detailed analysis of the impacts of management decisions on both land and aquifer status, as well as aquifer impacts on management decisions. The coupling by Chan *et al.*, (2010) of BNs with an ecological risk assessment (ERA), illustrates the combination of risk methodologies, ultimately contributing to the development of risk management plans.

A new integrated methodology has recently been proposed by Farmani *et al*. (2008) and applied by the same team (Farmani *et al.*, 2009) on the work undertaken in the GW case study in Denmark (Henriksen *et al*., 2004). The integrated methodology is based on BBN and evolutionary multi-objective optimisation (EMO), which combines available evidence and evaluates the implications of alternative actions for water resources. The integrated methodology was able to address the uncertainties associated with decision making related to human behaviour, whilst also introducing boundary constraints on the probabilities of state values for the variables. Farmani *et al.* (2009) conclude that the EMO offers a population based, high performance and robust search technique, which can incorporate input from multiple decision makers within the search for optimal actions within the decision making process. Integration of the optimisation algorithm with the BBN is new, and has subsequently been used to retrospectively validate the use of BNs for the Denmark case study, checking for errors or inconsistencies, as applied previously by Henriksen *et al.* (2004) within the MERIT project. In addition, the use of BNs and EMO has also recently been applied within the Altiplano case study (Molina *et al.*, 2011a), which has facilitated effective stakeholder engagement in the design and evaluation of BNs consistency, whilst also incorporating conflicting interests.

The issue of managing conflict between stakeholders engaged in decision making regarding water resource management, has been supported as indicated previously through the use of BNs, where different perspectives of stakeholders can be incorporated within the design of a BN. Early applications of BNs incorporated different variables to represent stakeholders concerns and perspectives, although the more recent developments of using EMOs, offer increased opportunities to include multiple perspectives of stakeholders to inform decisions. This is a developing area, which is looking very promising to increase consistencies in BN/ OOBN applications whilst offering greater inclusion of stakeholders perceptions of the problem domain, to facilitate negotiations with stakeholders.

Of interest within the current research, a Participatory Integrated Planning (PIP) procedure was proposed and demonstrated by Castelletti and Soncini-Sessa (2006) to facilitate negotiations for water management in line with the requirements of the WFD. The procedure requires both "informative" (gathering information from stakeholders) as well as "active" (stakeholders act as decision makers making decisions) participation through 10 steps. Within this process BNs are suggested as a possible tool to be incorporated in Step 3 "model identification", although of specific interest is the preparation stage in Step 0 which requires the identification of the "preliminary objectives and activities", and hence an understanding of the problem to be tackled. At this step, the project objectives are defined, water system boundaries are identified (time and space), the characteristics of the context in which the decision is to be made, and the identification of the available data and stakeholders. Once this stage is complete, this is followed by further identification of variables, selection of a model (e.g. BN), and analysis of options to inform a decision maker to make a decision. This PIP procedure has been successfully applied to the Vomano water system, which included BNs as a modelling tool (Castelletti and Soncini-Sessa, 2007c). In this application, BNs were proven to be a flexible tool, to objectively address conflict in a situation, and develop social learning through encouraging engagement in the decision making process.

Ticehurst *et al.*, (2007) also developed a BN based tool for stakeholders to use to inform decision making. The stages involved: a review phase, identification of BN structure, action development, populating CPTs, model validation and verification, software development and distribution. Within this study, Ticehurst *et al.* (2007) developed a user-friendly software platform to enable application and testing by stakeholders to encourage the engagement of stakeholders in the use of BNs. The software utilised the Interactive Component Modelling System (ICMS) using embedded C-like language (Reed *et al.*, 1999). These developments indicate the steps being taken to seek and support active involvement in decision making using BNs, and their subsequent development within specific software tools for end-users.

The use of outputs from hydrological models as inputs to BNs are recognised to be beneficial where BNs can provide the evaluation of policy options, whilst also incorporating potential impacts in relation to a hydrological system (Martínez-Santos *et al.*, 2010). The use of outputs from numerical models, (informed based on "hard" data), would increase the credibility of BNs as a tool as perceived by stakeholders (e.g. farmers, water authorities, policy makers), to support the evaluation of policy options and their impact on hydrology. Molina *et al*. (2011b) have also successfully applied BNs coupled with a groundwater flow model for the Altiplano water system. These applications of BNs coupled with "hard" models suggests the flexibility of BNs to incorporate various data types, and integrate with other models, is a clear advantage.

Many techniques can be combined with BNs, including system dynamics, coupled component models, genetic algorithms and meta modelling. Farmani *et al.* (2009) have identified that the environmental sector has seen an increase in the numbers of simulation and statistical tools which are coupled with information systems for the purpose of integrated assessment and management. The developments reviewed above illustrate the integration of BNs with other techniques is becoming an evolving area. In order to make use of these tools awareness and education of stakeholders and decision makers needs to be enhanced, to ensure they understand how these developments are being applied to the decision contexts within which they operate.

2.6 Benefits and challenges of BN

In the foregoing sections, the contexts and methodological approaches used for the application of BNs were discussed whilst also highlighting beneficial aspects and drawbacks of the technique. The benefits and challenges of the use of BNs for environmental and water resource management are drawn together within this section, to provide an overview of the performance and application of BNs. Table 2.1 highlights these features, which includes points made from three recent review articles (Kumar *et al.*, 2008; Zorrilla *et al.*, 2010; Barton *et al.*, 2012) and articles from the case studies reviewed. Features against which the benefits and challenges of BNs are assessed include those related to both the operation and performance of BNs. Although BNs offer many advantages, there are still many challenges to be addressed for their further application, and this is the subject of continuing research within this field.

Table 2.1: Benefits and challenges of BN applications

	Benefits	Challenges
Problem domain suitability	• BNs are applicable to unstructured problem domains, with a limited number of variables, and without dynamic applications [6] • BNs can be used for cost-benefit assessment [8] • BNs useful for risk analysis [19] • BNs useful for describing and exploring the relationships between actions and indicators [19] • Used for scenario analysis and "what if" questions [19] • Useful in addition to other deterministic modelling tools (e.g. for hydrological assessments) [19] • Useful for modelling the implications of the WFD [19]	• BNs not necessarily suitable where deterministic relationships between variables are known (hence limited uncertainty between the relationships) [6] • BNs not necessarily useful for a "system model" (e.g. groundwater flow) with a focus on reliable predictions [19] • BNs may not always be suitable depending on the stakeholders experience in using mathematical models, and the characteristics of the problem aspect to be modelled [26]
Contextual application	• Useful as a strategic planning tool as well as specific locations [1, 10] • Useful for long term strategic water management [17] • Able to evaluate trade-offs between social, economic and environmental impacts of policy options [19]	• Inclusion of temporal changes can be problematic [1,2,5,19] • Inclusion of spatial dependencies can be problematic [5] • Separate BN models would need to be constructed for separate catchments/ aquifers [5,22]
Integration of disciplines	• Able to integrate diverse variables (e.g. political, social, cultural) [1,5,8, 10, 17, 23]	• Data to evidence relationships between different disciplines may be limited [1]
Integrated assessment	• BNs supports the principles of integrated assessment [19, 22, 23]	• Involvement of a wide range of experts to provide knowledge on the integration of the disciplines is required [19]
Decision makers	• Enables and supports rational and informed decisions to be made by decision makers [10, 19]	
Complexity	• Limiting the level of complexity and detail enhances the applicability for non-specialist users [5]	• Problem domains for water resource management are typically complex, with large BNs being developed [5] • May need to reduce complexity through parent divorcing [11]
Uncertainty	• BNs represent uncertainty in a transparent and practical way through probabilities [10, 22] • Can handle uncertainty in data or lack of understanding of the system [17]	• Uncertainty may be present in the causal structure itself, parameter or natural uncertainty within the probability distributions [11]

	Benefits	Challenges
Communication	• Visual representation of the problem domain which communicates an understanding of the system as a whole [1, 26] • Visualisation of cross benefits between management measures enhances the effectiveness of planning [5] • BNs provide an interactive transparent framework which enhances communication [8, 26] • BNs could promote social learning, and span the gap between researchers and policy-makers.[8] • Facilitate the exchange and representation of perspectives of a problem from different stakeholder groups [10, 17, 18, 19, 26] • Able to defuse potential conflicts between different viewpoints [17, 18, 19]	• Feedback within systems is difficult to represent [1] • Acceptability of BN may be acknowledged without complete understanding of limitations [1, 19] • Understanding of BN use of probabilities when stakeholders may be familiar with other modelling techniques (e.g. deterministic modelling) [7] • Difficult to understand for non-experts [10] • Not always appropriate for large models, where each stakeholder perspective would need to be reflected in a utility node within the model [6] • Need to have good communication skills, effective skills in seeking participation of stakeholders, and psychological awareness of group behaviour and relationships [10]
Transparency	• Used as a participatory tool, BNs offer transparency in decision making [1] • Environmental decision making is able to be made more acceptable to the general public. [1] • Provides a framework for models, monitoring data, and domain expert knowledge to be analysed [8, 26]	• Difficult to ensure stakeholders understand the principles of BNs [1] • Could be open to political manipulation [1]
Model sensitivity	• Able to explicitly represent model responses to the resolution of the probability distributions [2]	• Increased resolution of probability distributions can increase sensitivity within the model, although demand more data to inform CPTS. [2, 11] • Cumulative uncertainty and hence insensitivity of variables to management measures [11]
Scenario modelling	• Management options can be modelled within a short-timescale [1, 16] • Multiple management options can be included [1, 26] • BNs can support context dependent decision analysis [2]	• Large networks may require large amounts of data [1] • Over extrapolation of scenario predications may occur compared to the supporting evidence. [1]
Data type	• Wide range of data can be used (e.g. expert opinion, or ‘model outputs’) [1, 19] • Both “hard” and “soft” data can be used [19]	• Could place too much reliance on uncertain data, rather than accurate data records [1, 19] • Experts may be unwilling to provide options. [1, 4] • Continuous data (e.g. phosphate concentration) needs to be discretised [4] • Data used to represent “current knowledge” needs to be independently verified to ensure its credible [12]
Data availability	• Able to use incomplete data sets to model problem domains [1, 19] • Able to use BNs to highlight missing data and knowledge [8]	• Incomplete data sets used to inform CPTs would increase uncertainty within the BNs [1] • Need to involve experts to provide data sources [10, 19] • Expert opinion may be unreliable [27]

	Benefits	Challenges
Time required	• Can be quick to update [1]	• The limited amount of time for stakeholders to participate in BNs development is a constraint [15] • Time intensive for stakeholder group and process manager [19]
Casual structure development	• Able to use large data sets to inform BNs structure (e.g. structural learning) [1, 2] • Use of combined prior knowledge and data learning algorithms to inform BNs structure [2] • Alternative casual structures can be developed [2] • Able to use OOBN to model problem domain [2] • Causal structures between variables is relatively easy [10]	• Structural learning difficult to understand by non-experts [1] • Could be manipulated [1] • If using structural learning the structure may not represent reality, as the relationships are only determined by relationships between the datasets used to inform the network [13] • The 'right' network structure needs to be designed to elicit meaningful probabilities [4] • Incorporation of dynamic network models can lead to an exponential increase in size [4] • Need to use additional data and test the BNs to check uncertainty in model structure [11]
Dynamic modelling	• Can incorporate time-steps [28,29]	• Can become complex and difficult to update dynamic structures [11] • BNs are regarded as "static" tools without iterative mathematical solvers [19]
Spatial modelling	• OOBN can be used to represent the problem domain at different scales [20,21]	• BNs focus on probabilistic modelling, not spatial modelling [19]
Object Orientated Bayesian network	• Different expert groups can populate the sub-models, which can be linked together to describe the whole system [11,22,23] • Can use BNs as OOBN to represent decisions and impacts at different scales [20, 21,22] • Individual sub models can be connected up into an overarching OOBN [22, 23]	• Model complexity can increase, therefore parsimonious models are advocated [11] • OOBNs are still an emerging in use of water resources management, and not widely known [20]
States of variables	• States can be represented as Boolean, labelled, or numbered [21] • Able to use states to represent break points of management requirements [11]	• Restricted discretisation of states, may result in increased uncertainty [11] • Many discretised states can result in large data requirements, and more complex model developments. [11, 12]
Updating	• Rapid updating can be achieved within the model to incorporate new evidence [1, 19] • Expert derived probabilities can be updated over time given new information, from multiple sources [4].	• Documenting the assumptions and evidence sources used within the model is required to ensure interpretation by other modellers or water managers [1] • Updating beliefs across a large network [4]

	Benefits	Challenges
Participatory approach	• Useful for structuring meetings and encouraging communication and discussion [3] • Support communication and social learning in participatory planning [5, 16, 19, 20, 26] • Individual or small group meetings can be more beneficial compared to groups > 5 people [9] • Active involvement of stakeholders is facilitated using BNs [10, 20] • BNs provided opportunities for open debate amongst stakeholders [10, 18] • Opportunities for collaborative model building [15] • Participation can be used in the design, validation and use of BN [16] • Local end-users to the catchment, as well as experts can be included [16] • Involving stakeholders can generate trust in the use of BN [16]	• An understanding of probabilistic models is required by the user to facilitate stakeholder inputs [3, 10] • Training of stakeholders in the use of BN is required [10, 15, 18] • Time available by stakeholders is a limiting factor [3, 15, 19] • May require an independent facilitator for large groups of >5 people [9] • Facilitation is required specially for conflict settings [19] • Need active involvement of stakeholders to ensure representative and valid construction of the BN occurs [10]. • Need to have a stakeholder engagement plan drawn up (mission statement, timescales, resources, milestones) [10] • Stakeholders need to agree on a common goal, without which participation cannot be continued [19] • Confidentiality may need to be ensured to encourage participation [19]
Outputs from a BN	• Probability distributions allow the level of uncertainty to be explicitly represented [3] • BNs make apparent the presence of significant uncertainties represented within the predictions, which are increased in the presence of multiple drivers for change [3] • Prioritisation of management options [16]	• Familiarity with absolute numbers, rather than probability distributions may affect the communication and interpretation of the results. [3] • Transferability of a BN is limited, with individual BNs required for individual catchments/ applications [5]. • BNs outputs should be reviewed by an expert for consistency [10] • Stakeholders need to be trained in BNs to ensure they understand and can give feedback on the BN [15, 18] • Credibility of the modellers and their communication skills present and important component to the success of the results [19]
Validation of BN	• Individual data sources for current conditions are used to populate the variables, states and CPTs to validate the model behaves as expected [9]. • Involvement of stakeholders provides credibility of BNs developed, as they are accepted by stakeholders [10, 14, 16, 19, 23]. • Can use adaptive management, third party expert opinion, sensitivity analysis to validate a BN [11] • Can use stakeholders perspectives of the acceptability of the BN to represent the system adequately, hence user validation [20, 23] • Compare results to other studies using different methods for the same problem context [23] • Could use EMO to evaluate consistencies in a BN [24]	• BNs are usually applied to future events, which do not have data available and hence cannot be fully validated [9, 11, 14] • Need to involve experts, stakeholders and citizens to give credibility to the BNs [10, 16] • Need to use additional data and test the BN to check uncertainty in model structure [11] • Difficult to validate completed BNs using independent data [11, 14] • Stakeholders may not fully understand the mathematical functions in BN [19]

	Benefits	Challenges
Coupling of BN with other methods	• BNs can be coupled with other methods, especially to enhance understanding where limited data is available [5,6, 19, 20] • BNs coupled with other techniques provides a structured approach to planning issues for catchment management [5, 19, 20] • Coupling with techniques such as GIS could increase application of BN for spatial and temporal applications [8] • Coupled with EMO provides more informed evaluation of management options [9,24] • BNs (a "soft") technique can be coupled with other "hard" techniques (e/g/ groundwater flow models/ agro-economic models) [25]	• BNs alone may not be as credible for adaptive IWRM without coupling with other hydrological models [19]
Software	• Recognised software providers, gives credibility to the approach [19]	• Requires trained people to use it [16] • Some software requires purchasing, restricting access to wealthy public/private organisations [16]
Note: [1] Bromley, 2005, [2] Barton *et al.*, 2012, [3] Zorrilla *et al.*, 2010, [4] Kumar *et al.*, 2008, [5] Holzkämper *et al*., 2012, [6] Castelletti and Soncini-Sessa., 2007b, [7] Bromley *et al*., 2005, [8] Henriksen *et al*., 2007a, [9] Farmani *et al.*, 2009, [10] Henriksen *et al*, 2007c, [11] Barton *et al.*, 2008, [12] Ames *et al*., 2005, [13] Pike, 2004, [14] Ticehurst *et al.*, 2007, [15] Ticehurst and Pollino, 2010, [16] Martin de Santa Olalla *et al*., 2007, [17] Zorrilla *et al*, 2007, [18] Henriksen *et al*, 2007b, [19] Martínez-Santos *et al*., 2010; [20] Carmona *et al* 2011a, [21] Carmona *et al*., 2011b, [22] Molina et al (2009), [23] Molina et al, 2010, [24] Molina *et al*., 2011a, [25] Molina *et al.*, 2011b, [26] Castelletti and Soncini-Sessa (2007c), [27] Reckhow *et al*., 1999., [28] Barton et al., 2005; [29] Shihab and Chalabi., 2007.		

2.7 Organisational perspectives of BN

Published articles on the perspectives of organisations in the use of BNs are very limited, even though such assessments would provide an important reflection on their perceived use for application to water resources management. This is especially so with regard to the prevalent increase in the use of BNs for water management reported in the academic literature. One publication by Henriksen and Barlebo (2008) reviewed the use of BNs as applied to Adaptive Management (AM), through an ex post interview with two water managers from the Danish water company involved in the Danish case study as part of the MERIT project. The success of BNs was reviewed against the following criteria to establish whether BNs were able to:

- facilitate Adaptive Management and allow water management to proceed in the face of complexity and uncertainty;
- provide support in the development of a shared understanding of the system to be managed and provide a structured process of learning;
- support the transition from the currently prevailing regimes of river basin water management into more adaptive regimes that are better able to deal with changing conditions.

The water managers viewed the use of BNs as an approach positively, but reported that the use of BNs required the appropriate space and time to be assigned to actively reflect on water management issues (e.g. groundwater water management). The day to day activities of the water managers was previously identified as the main inhibitory factor in analysing and understanding the problem of groundwater management. Although construction of a BN required both time and space to be set aside, the process of understanding and causally representing the problem domain effectively enhanced the water managers understanding and awareness of GW management. Specifically, by using the forums (and hence linking to the stakeholders) involved in the use of BNs, the water company found it did not need to contact the 50 farmers separately to explain the voluntary farming contracts being considered for groundwater management. Therefore, the water company was able to become more effective in evaluating the management options available, due to a greater understanding of the influencing factors affecting the management of farming activities, as well as evaluating their cause-effect relationships.

Further areas for development of the use of BNs as identified by the water managers at Copenhagen Energy (CE) within the Danish case study included:

- more time should be allocated to improved and interactive training of all stakeholders involved in the development of the BNs to allow for greater understanding and engagement in the process;
- the use of a facilitator to manage the multi-stakeholder workshops and meetings to avoid political positioning of the stakeholder representatives;
- further potential integration with geographical information systems (GIS) to increase engagement with stakeholders in the process.

These water managers also recognised the benefits of using structural learning as a function within a BN, which allows for a more spontaneous and interactive engagement with the development of the BN between the various stakeholders.

Stakeholders involved in the Upper Guadiana Basin case study who used BNs and latterly coupled agro-economic models, indicated a high degree of satisfaction and interest in the methodology, which promoted increased participation (Carmona *et al.*, 2011a). Such enthusiasm may however be moderated by the job role or function held by individuals as demonstrated by Inman *et al.* (2011). In this study, end-users who were involved with or directly affected by policy decisions perceived BNs to be more effective, than end-users with a research or engineering background. The study by Inman *et al*. (2011) does not, however, highlight specific organisations, instead concentrating on job function or background, and was limited to only nine end-users perspectives.

An enthusiastic response from UK participants involved in the development of BN reported by Holzkämper *et al.* (2012) identified the following perceived benefits of BN use:

- provides a structured approach to address complex planning issues and integrate knowledge from different domains
- the visualisation of cross-benefits between management measures enhances the effectiveness of planning

- the presentation of uncertainties allows for systematic review and identification of robust measures
- limiting the level of complexity and detail enhances the applicability for non-specialist users
- the tool could support communication and social learning in participatory planning.

However some initial responses in the management of natural resources as reported by Ticehurst and Pollino (2010) highlighted that the development of capability within organisations (government agencies) to conduct decision support using BNs, was not necessarily successful. The limitations of stakeholder time and data availability were among the most reported reasons for limited use of BNs. This experience highlights some real world issues which present possible future constraints on the use of BNs for water/ natural resources management. The focus in the study by Ticehurst and Pollino (2010) recognised that the capacity building approach, through developing knowledge on BNs within the government agencies, was less effective as compared to a collaborative approach, where BN development was not solely managed by the government agencies. These findings are important to consider in the future development of BNs, especially in light of the recent successes experienced in Spain, which has been achieved through a more collaborative approach.

Although these perspectives offer an insight into the use of BNs by end-users, further research is required to provide a more balanced view of organisational perspectives and hence the extent of BN acceptability for decision support.

2.8 Main findings and gap in knowledge

Through the review of the literature in the previous sections, significant findings have been revealed. These are subsequently highlighted through answering the questions posed at the start of this chapter.

"*In what contexts have BNs been applied and what were the outcomes of their application?"* (Section 2.4),

BN have been applied to water quantity (e.g. water demand for domestic and industrial purposes) and water quality issues (e.g. chemical concentrations – pesticides, phosphorous, nitrogen) for both surface water (lakes, reservoirs, rivers, estuaries and oceans) and groundwater bodies (aquifers). The spatial scale of application has also varied, with applications targeted at the catchment level, as well as focused on the treatment (for domestic supply) and supply of water (for both domestic and industrial supply).

Through the case studies reviewed, the main findings regarding the extent of BN application to model water quantity issues are:

- BNs have been demonstrated to be useful for informing the management of both domestic and industrial supply.
- BNs have been able to combine both SW and GW within the same model.
- BN applications for the study of water quantity management have been dominated by research from organisations within Europe, through EU funding.
- Application of BNs, specifically within a water utility to manage domestic supply, has not been reported in the academic literature to date.

The main findings related to the use of BN applications to water quality applications, are:

- A limited number of papers have been published concerned with water quality in GW or SW compared to water quantity applications.
- BNs have been applied to address water quality issues at both the catchment level (e.g. pesticides in GW, phosphorous in SW), and for water treatment process applications (e.g. for reverse osmosis treatment).
- BN are useful in both low technology countries (e.g. West Africa) as well as more developed countries (e.g. Norway, Denmark) to inform water policy developments
- BNs incorporating both GW and SW quality issues have been published.

- BN have been applied to incorporate conflicting opinions of stakeholders in the management of water quality (e.g. pesticide management).

The combination of both water quality and water quantity issues within BNs has been limited. Only six articles related to five separate case studies have been identified. Of the five case studies, only two combine SW and GW (Varis and Lahtela, 2002; Chan *et al.*, 2010). Hence, the lack of knowledge in the application of BNs for these combined problem domains, demands additional research to determine the suitability of BNs to support decision making under these conditions.

The use of BNs with stakeholders in the NeWater and MERIT projects, specifically the Spanish groundwater quantity study and the Danish groundwater quality study, were more comprehensive with greater representation of stakeholders influencing the management of water resources. Therefore as examples of the use of BNs for both participatory and integrated water resource management, these published reports are more reliable and their continued application within the same case study areas has generated a long-term interest in the use of BNs as a successful water resource management technique.

"*How has participation with stakeholders in the application of BNs been conducted and how useful has this been*?" (Section 2.5.1)

The range of approaches to the inclusion of stakeholders in BNs development highlighted in Figure 2.5, indicated a breadth of techniques can be used. In some instances the use of participation was not used as the purpose of the use of BNs in these contexts were for methodological development, initial demonstrations, or for optimal treatment operation or selection. However at a more strategic policy level, to inform decisions regarding the management of water resources, participation was used in the majority of cases reviewed.

Participation has been useful to generate knowledge and awareness amongst the stakeholders represented in the case studies where BNs have been used, which have predominantly been as a result of the MERIT and NeWater projects. Although limited conflicts between stakeholders have been reported, the use of BNs was recognised to have potential to accommodate multiple stakeholder preferences, and hence facilitate potential conflict negotiation within a BN.

Limitations in the use of BNs as a participatory technique have been acknowledged to be related to: i) a lack of resources, ii) lack of rules of participation, iii) a lack of support and in-depth involvement of authorities, iv) a lack of hands-on use of BNs by stakeholders, and v) a lack of professional supervision of the process of BN use. Although BNs are recognised to offer rich learning opportunities with a view to developing long-term sustainable practices by decision makers and stakeholders, these identified constraints need to be pragmatically considered at a practical level. This is especially the case when investment is needed to develop the capability of stakeholders in the use of BNs, or in gaining the commitment of organisations to employ additional personnel. Therefore, as with the introduction of any decision support process, the sustainable use of that intervention needs to be considered.

The range of organisations involved in BN applications has varied. BN application within the water sector has been very limited, with only a few academic developments being conducted through research projects where water companies have been involved as stakeholders. Only one study focused on the development of BNs in association with a water company to inform potential investment strategies for the protection of groundwater for domestic use in Denmark (Henriksen *et al.*, 2007c). This study did not involve the development of a BN decision process for the organisation, instead focusing on the academic application and development of a BN to be applied through a participatory approach to support adaptive decision making for integrated water resources management.

In the UK, BN application has been very limited, with no water company applications of the technique identified to date, although initial engagement in the development of the technique within the water sector was conducted by Bromley *et al.* (2005). Recent initiatives which involved the development of a BN based meta-model for integrated catchment management (Holzkämper *et al.*, 2012) supported by the UK Environment Agency, in addition to another study focused on marine planning by Stelzenmüller *et al.* (2010) supported by DEFRA, highlight the growing interest in the use of BN as a technique for integrated management of natural resources, within the UK.

"How have dynamic Bayesian networks (DBNs) and object orientated Bayesian networks (OOBNs) been applied in water resources management and are these applications successful?" (Section 2.5.2)

BN applications have mostly focused on single time periods (e.g. one year), or in some cases not mentioned the temporal period for the BN. BNs have been known for their limited ability to incorporate dynamic modelling of problem domains, although the use of a time-step approach to structuring the BN can be used to represent the time dimension. A few case studies have now emerged to highlight the use of BNs incorporating a time-step to reflect multiple time periods (e.g. multiple years). Criticisms of the use of DBNs include the increased complexity involved in the representation of the network and the additional uncertainty associated with the subsequent time steps, for which limited or no information is available. However, to model management decisions, which are made cumulatively over time (e.g. through the PoMs as part of the WFD implementation), representation of the outcome of previous management decisions need to be factored into the BNs to inform subsequent decisions to be taken with regard to the management of water resources. This is still an area for further development.

OOBNs on the other hand have only just started to be reported in the academic literature for water resources management during the last couple of years (Carmona *et al*., 2011b). These developments are related to the incorporation of multiple 'units' of network 'substructures' (e.g. aquifer sub-structures and farm scale sub structures) which are incorporated to assess the implications of management measures across multiple scales (the aquifer scale and farm level scales). The incorporation of these substructures represents the start of a new era for exploring OOBNs use within Water Resources Management (WRM), for which further research is required before the full extent of the applicability of OOBNs can be determined. No application of OOBNs has been reported within the academic literature reviewed for the management of potable water within a water company, as yet and therefore highlights a further opportunity for additional research.

"*In what way, and how effectively have BNs been coupled with other techniques*?" (Section 2.5.3),

The rise in the applicability of BNs to address water resources management decisions has also driven the coupling of BNs with other techniques. These have included 'soft' techniques (e.g. problem structuring), and 'hard' techniques which include coupling of algorithms to inform BN structures, or incorporation of output data from other models to directly inform states of variables, or relationships between variables within BNs. The coupling of methods with BNs has enhanced and increased the credibility of BNs as a technique to incorporate existing modelled data where available. Through linking multiple data sets multiple stakeholder groups are able to be more involved to directly see how data they are more familiar with is used to inform decisions regarding the management of water resources. Although the development of coupled techniques with BNs is still relatively recent, further research in the development of BN based processes would add to the debate of their suitability and applicability for differing stakeholders (e.g. water companies as opposed to government agencies).

"*What are the benefits and challenges regarding the use of BNs for water resource management?"* (Section 2.6)

Through the detailed analysis of 29 articles Table 2.1 has indicated a wide range of benefits and challenges associated with the performance and operation of BNs. The main findings related to these benefits and challenges are summarised in Table 2.2.

Table 2.2: Summary of main benefits and challenges of BN use for water resource management

Main benefits	Main challenges
• BNs are suitable for unstructured problem domains, and able to conduct scenario analysis. • BNs suitable for a strategic planning tool. • Able to include diverse variables. • BNs support integrated assessment. • BNs support participatory decision making. • BNs represent uncertainty in a transparent way. • BNs allow for visual representation of the problem domain, which encourages communication with stakeholders. • Management options can be included to assess the implications on the system being modelled. • Multiple sources of data can be used. • Potential to incorporate time steps (DBNs) and multiple repeat component OOBNs. • BNs can be updated quickly with new evidence. • BNs can be coupled with other models to increase credibility and enhance understanding where data is available. • Multiple software providers now give credibility to the use of BNs as a technique.	• BNs are not always suitable as a technique especially where data is already available. • Difficulty in representation of spatial and temporal problem domains. • A wide range of experts is potentially required to inform the BNs. • Uncertainty will not be removed entirely with structural as well as variable and data uncertainty still present. • Difficult to ensure stakeholders understand BN approach. • Large networks can become complex • Time available by informants may be limited. • Data may be limited to inform structural learning • Updating complex structures may be problematic • Transferability of BNs to other catchments/ locations may be difficult. • Validation can be difficult for BNs where no data exists or management options have not been put in place before. • Trained people are required to develop a BN using software.

"What organisational perspectives have been disclosed on the use of BNs in relation to water resources management?" (Section 2.7).

There are a limited number of articles identifying the perspectives of the end-users on the use of the BNs as a decision support tool, which clearly indicates a gap in knowledge on the perceived use of BNs. However, of the reports published one water company has supported the use of BNs as a participatory technique to encourage active debate amongst influential and interested stakeholders regarding the long-term management options for GW quality. Perspectives offered by a government agency on the use of BNs also highlighted the benefits of the visualisation of management measures and relationships with other variables, and recognised the role BNs could offer to support social learning in participatory planning.

Specific areas for further developed of BNs identified by water managers were: i) increased amount of time available for training of all stakeholders involved, ii) requirement of a facilitator to support the engagement with stakeholders in the use of BNs, iii) additional developments of GIS in association with BNs to enhance stakeholder interaction and generate associations between management actions and the physical landscape context.

2.8.1 Gap in knowledge and focus of research

The BN applications reviewed have highlighted that BNs although becoming widely regarded as a new tool for water resource management, have only seen significant developments in the academic arena in the last few years. Actual use by organisations for the management of water resources has had limited coverage in the academic literature. Further application of BNs within organisations for the management of water resources would provide insight into their suitability for practical use by water companies or environmental regulators.

Limited application of BNs within the UK highlights a gap in knowledge regarding the usefulness of the practical application within the UK water sector in relation to the constraints of the governance of potable water supplies by government agencies. Hence, further exploration of the use of BNs as part of a decision support process within the water industry in the UK is required. Specifically the application of BNs to understand and inform organisational decisions in response to the implementation of the EU WFD would further contribute towards the debate on their suitability for informing decisions regarding the management of water resources.

The need for decision makers to be able to make informed strategic decisions in response to the WFD implementation and its impact on investment in water treatment and water protection, is pressing. No current decision support process or system exists for use in the water industry within the UK to address the implications of the WFD and hence further research and development in this area is required. The research reported within this thesis therefore contributes the first engagement of the use of BNs within a water company for investment planning in the UK. The research will provide an assessment of the impact of the EU Water Framework Directive on a case study UK water company – Anglian Water Services Ltd (AWS), using BNs as a technique to inform the strategic management of a regional potable water supply.

2.9 Summary

A review of the development of decision support tools and current research regarding the use of Bayesian networks for decision support has been presented. The application contexts, methodological approaches together with organisational perspectives, benefits and challenges of the technique have been presented, which address RQ 1.1 and RQ 1.2. The knowledge base to which the findings from the current study can be related has therefore been presented. The following chapter presents the research strategy and methodological approach used alongside an introduction to a UK water company used as a specific case study within this research.

3 Research approach and methods

3.1 Introduction

The research challenge involves the development of a BN based Hybrid-DSP to analyse the implications of the WFD for the management of potable water supply and hence inform water company organisational responses, as discussed in Chapter 1 and 2. The dynamic context for the research presented some challenging issues to manage. These included: the continuous changes (e.g. structural – business units, procedural, personnel) within the case study organisation; changing levels of knowledge by water managers in the water company regarding the incremental implementation of the WFD at both national and regional level; the development of organisational and researcher understanding with respect to these contextual changes; and the iterative development of the Hybrid-DSP. Within this context, a number of research approaches, strategies and methods were considered, and evaluated. This chapter presents and discusses these approaches and methods. An overview of the research process and the corresponding methods to answer the specific research questions in Section 1.5 are illustrated in Figure 3.1, and are discussed in the following Sections.

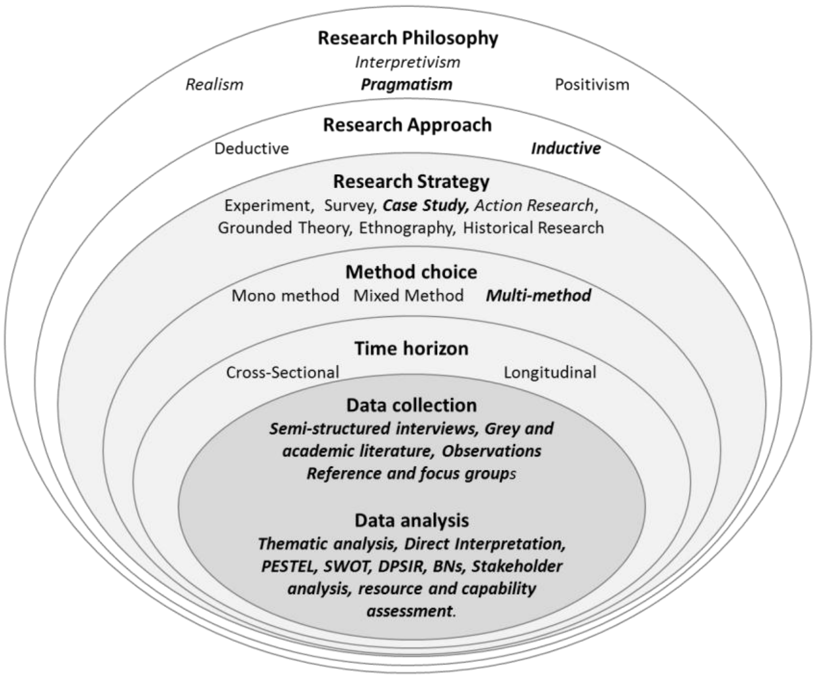


Figure 3.1: Overview of research process (adapted from Saunders et al, 2009)

3.2 Research philosophy

The philosophical position taken to conduct research has implications for the nature of reality (ontology), how knowledge is gained (epistemology), how values are considered in research (axiology), the research process (methodology) as well as the language used within the research (rhetoric) (Saunders *et al*., 2009, Cresswell and Plano Clark, 2011). Hence, the philosophy (also known as a 'worldview' or 'paradigm', [Cresswell and Plano Clark, 2011]) concerns a set of assumptions and beliefs which inform the study, and how new knowledge is generated and understood. A range of philosophies can be used including; positivism, postpostivism, constructivism, realism, interpretivism and pragmatism. This research is concerned with pragmatism, which takes the view that the research question is of primary importance and hence determines the ontological and epistemological perspective used in the research (Robson, 2002; Saunders *et al*., 2009). The questions may not directly relate to only one philosophy, with multiple philosophies being incorporated, therefore the worldview of 'what works' in practice is adopted by the researcher (Robson, 2002). This tradition has consequences for the methods adopted, which are generally multi or mixed methods to address the questions posed (Cresswell and Plano Clark, 2011) (see Section 3.6).

3.3 Research approach

3.3.1 Inductive-deductive

Research can be conducted through either an inductive or deductive research approach or a combination of the two. Theory is either derived from data (inductive) moving from specific details to a generalisation, or theories are observed with conclusions drawn (deductive) which involve the general theory being applied and tested within a specific context (Robson, 2002). The specific features of the two approaches are highlighted in Table 3.1.

Table 3.1: Features of deductive and inductive research approaches (adapted Saunders *et al.*, 2009:127)

Deductive approaches concerned with…	**Inductive approaches concerned with..**
• Scientific principles • Moving from theory to data • Explanation of causal relationships between variables • Collection of quantitative data • Application of controls to ensure validity • Operationalization of concepts to ensure clarity of definition • Highly structured approach • Researcher independence of what is being researched • Necessity to select samples of sufficient size to generalise conclusions	• Gaining an understanding of the meanings humans attach to events • A close understanding of the research context • Collection of qualitative data • A flexible structure to allow changes of research emphasis as the research progresses • Researcher being part of the research process • Less emphasis on the need to generalise

Within this research an inductive approach was combined with a deductive approach to address different research questions (Figure 3.2). An inductive approach was used to understand the research context and to inform the design of a Hybrid-DSP. This required an understanding of the research context and the strategic challenges facing the UK water sector as well as region and site specific issues for a specific case study water company (see Section 3.4.3 Table 3.3). A deductive approach was also utilised during the testing of a BN based Hybrid-DSP, which was designed around the themes and issues inductively identified from the research context. Subsequently the further development of the BN based decision support approach incorporated an inductive component in the use of additional techniques to generate an enhanced Hybrid-DSP. This was an iterative process which is reflective of a flexible research approach as discussed in Section 3.3.2.

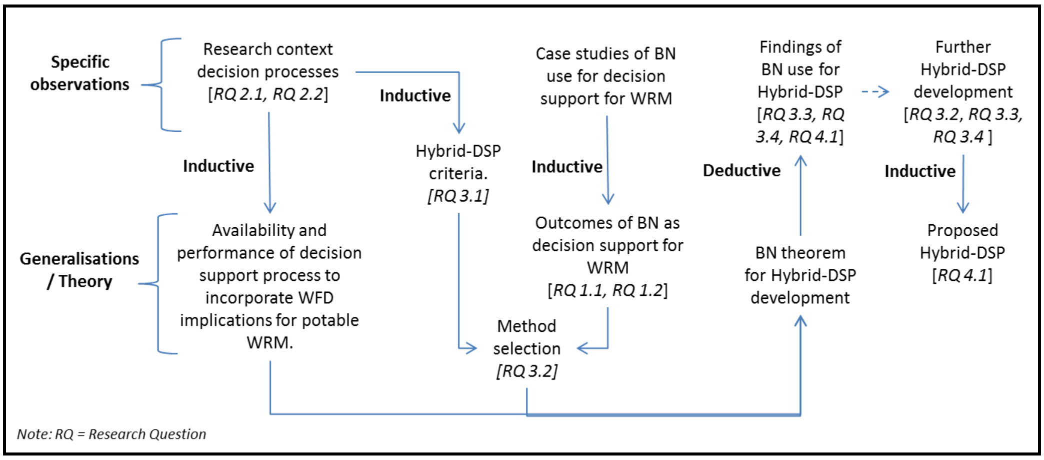


Figure 3.2: Inductive - deductive approach to the research

3.3.2 Flexible, exploratory and participatory research

A number of flexible, exploratory and participatory approaches were adopted throughout the conduct of the research in accordance with the selected dominant pragmatic philosophy. Both Robson (2002) and Yin (2003) recognise these approaches as complementary and consistent with qualitative applied case study research. A flexible approach to research involves no pre-specification of a research design template as is the case with fixed research designs; instead an adaptable stance is taken by the researcher to the research. Robson (2002) acknowledges that a flexible research approach places high demands on the researcher during the conduct of the research. He also recognises that consequently the quality of the research is aligned with the quality of the researcher and that prior knowledge of the tools and techniques used for social research enhances the research conducted. In addition, the personal skills of the researcher which include; "*having an open and enquiring mind, being a 'good listener', general sensitivity and responsiveness to contradictory evidence*" (Robson, 2002:168) provide a professional platform for the conduct of the research.

Through the adoption of an exploratory approach the researcher aims to understand a new situation or issue, as the study evolves. Neuman (1997) suggests that an exploratory approach does not always yield definitive answers to issues, but often supplies the basis for the development of further research. According to Neuman (1997), Robson (2002), and Yin (2003), the conduct of exploratory research (in association with flexible research), also requires the researcher to adopt an open mind, to be flexible, and make use of all available information. The nature of the data in these circumstances is also predominantly qualitative.

Participatory research is recognised by Robson (2002) as a form of action research (see Section 3.4), where collaboration is between the researcher and those being researched. Greenwood and Levin (2007) also advocate the benefit of participatory research through "co-operative inquiry" to co-generate knowledge with research participants. 'Engaged scholarship' is another approach posited by Van de ven (2007) which embraces and advocates participation. Participation allows for information to be shared with researchers, and participants to collectively generate knowledge which is used both with the development of the research or as an output in itself. Through the process of informing decision making, Lynam *et al*. (2007) identified three approaches to participation focused on extraction of information, co-learning, and co-management approaches, the selection of which would depend on the level of detail required to address the component of analysis. A drawback of using participation is the potential to obtain too much information which may lead to overwhelming complexity, where revised problem definition and design would be needed to guard against it (Lynam *et al*., 2007).

3.4 Research strategy

There are a range of research strategies which can be considered to conduct research, which include: experimental, survey, ethnography, grounded theory, action research as well as case study. These strategies are discussed in the sections below.

3.4.1 Research strategy features and suitability

An experimental research strategy requires control over events in order to be able to validly test a hypothesis, with such strategies being typically conducted through a fixed (i.e. fully controlled) research approach (Robson, 2002). The inflexibility of the experimental research approach to changes beyond the control of the researcher within the study context (e.g. WFD implementation, AMP development), presented a constraint for the selection of an experimental research approach. However some control over the development of the hybrid-DSP was held by the researcher through the application of the techniques in association with the water company representatives during reference group meetings and interviews (see Section 3.6.1, Table 3.7). Although, these instances were still limited and influenced by the dynamic research context.

Surveys allow for a range of research questions to be addressed, and therefore would complement a case study approach (Robson, 2002). However, Harrison (2009) argues that a survey used in isolation would not allow for the complexities and interconnections of the research context to be fully understood. Harrison (2009) also suggests that questionnaires, as alternatives to case studies, are also flawed due to the artificial disaggregation of variables into questions, which limits the representation dynamic and holistic nature of a case study setting and hence does not allow a true representation of the research context. Therefore, a survey or questionnaire used in isolation for the purposes of the research, would not be capable of eliciting the major influences on the development of a decision support process. Furthermore the use of surveys or experiments for this research would preclude active involvement and participation by the researcher in the development of a decision support process.

Ethnographic and grounded theory studies are also identified by Robson (2002) as alternative research strategies for flexible research designs. These approaches both support flexible research but have some further restrictions on use within the context of this research. Ethnographic studies provide a description and interpretation of the cultural and social features of a social group (Brewer, 2004). To achieve the objectives of the research, a full cultural study is not required, although some methods used within ethnography such as participant observation would be appropriate as a complimentary approach for data collection (Spradley, 1980; Denzin and Lincoln, 1998). Grounded theory, as a research strategy offers a procedure for generating theory through a systematic and co-ordinated process, which is used in applied fields of research (Goulding, 2002). The generation of theory from data, was not the focus of the research objectives, hence grounded theory as a research strategy was not selected.

Action research (AR) is a form of applied research which facilitates social change and includes the following characteristics: i) the people studied are active participants in the research process, ii) popular knowledge and concerns of ordinary people are incorporated, iii) examination of power relations and documents social inequality or injustice, iv) findings from the study are shared to raise awareness and empower ordinary people, v) research is tied directly to social-political action and achieving social goals (Neuman, 2011:30). Within organisations AR is recognised as an accepted method, which requires "*involvement by the researcher with members of an organisation over a matter that is of genuine concern to them and in which there is an intent by the organisation members to take action based on the intervention*" (Eden and

Huxham, 2002:254). Hence AR presents the opportunity for both engagement with participants and the cogeneration of knowledge through experience. AR also supports the use of multi-methods and aligns with a pragmatic research philosophy (Greenwood and Levin, 2007). However criticisms of the approach include its 'lack of repeatability', and hence lack of 'rigour', although this can be challenged through the depth and richness of insight into an aspect which is of importance to an organisation or group of people, which would not be obtained through other means. Within this research AR was adopted as a strategy to collaboratively understand organisational decision processes, the implications of the WFD and the subsequent iterative development of a Hybrid-DSP, with the intent of its application within the organisation.

Case study as a method of enquiry is well recognised within the field of qualitative research (Stake, 1995; Robson, 2002; Yin, 2003; Neuman, 2011). Within organisational research, case studies are recognised as an appropriate research method which allow for detailed analysis and insights regarding the management of the organisation and its development to be attained (Eisenhardt, 1989; Langley and Royer, 2006; Buchanan, 2012). In the field of organisational decision support, case studies have been successfully used to understand the development and application of decision support systems (e.g. Santhanam *et al*, 2000; Tian *et al*, 2005). Other studies in organisational change and decision making have also used case study as the basis of the research design. For example Fenton and Neil (2001) used a case study research approach in stimulating strategic change within an organisation. Yin (2003) notes that case studies may be viewed as a "less desirable form of inquiry" in relation to experiments and surveys. He lists the main arguments against the selection of a case study approach as i) the lack of rigour, ii) the limitation of scientific generalisation, and iii) case studies can be too long and can result in large unwieldy reports. These criticisms however can be balanced by the depth and richness of knowledge which is generated for a specific case, and within which direct and applied research can be undertaken within a 'real-world' environment. Flyvbjerg (2006) further claims the purpose of using case studies in research is to provide exemplar studies to contribute to the development of a scientific discipline, without which, he argues, the discipline would not be effective. Within the research, the context of the implementation of the EU WFD (although rooted in historical environmental legislation developments) as well as its implications for decision making by stakeholders including water companies responsible for water resource management, has a very contemporary focus which is suggestive of a case study strategy (Yin, 2003). In reference to the above, the selection of a case study research strategy for the purposes of the applied and participatory research is necessary to obtain a detailed understanding of the complexities of decision making in response to the current implementation of the WFD, specifically for the management of potable water.

3.4.2 Applied research within a case study organisation

In alignment with the flexible, exploratory and participatory research approach identified in Section 3.3.2, the research strategy adopted involves applied research within a case study organisation. The unit of analysis used within this research was the organisational decision making processes associated with the management of and investment in potable water treatment and supply (e.g. CRAGS, Asset Plus+ , Risk and Value [see Section 3.8]). Implications for the decision making processes from the impact of the WFD are studied and a Hybrid- DSP was developed to address these aspects (see Section 3.4.3). Consequently, the detailed insight gained from using a single case study approach enabled the research to be applied within the industrial setting of the research. A conceptual map of the case study approach and its contextual relationships is illustrated in Figure 3.3.

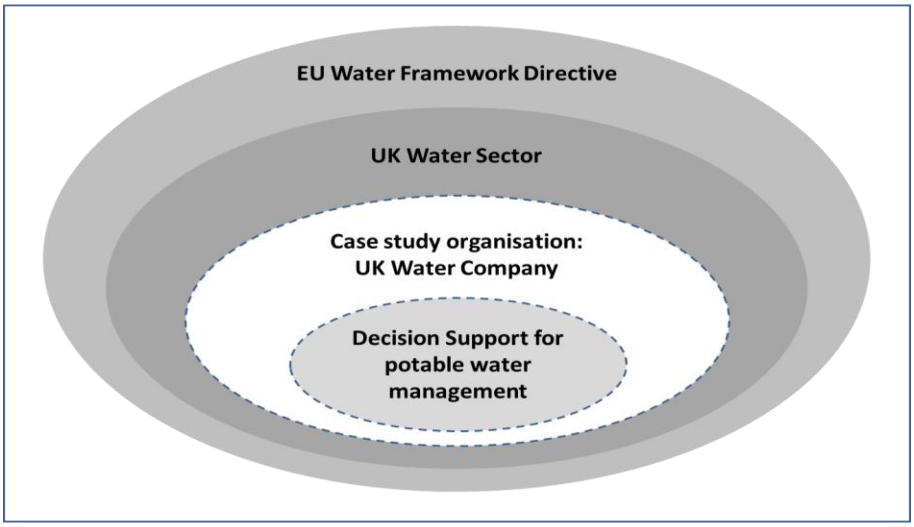


Figure 3.3: Conceptual map of case study context

An initial meeting on the 3rd Oct 2006, with the case study organisation and a reference group (RG) of informants discussed and determined the working arrangements and an initial plan for the conduct of the case study research. No pilot study was undertaken, as the research was focused on a single case study organisation. The practicalities of conducting research within the case study involved the identification of the procedures for data collection including access arrangements with the organisation (including offices, as well as operational field visits, use of organisational intranet and email), the resources available (people, documents, software), the data collection activities (e.g. discussions with informants, site visits, access to databases/ software, access to organisational documentation) and the period of time involved (which covered four years between 2006 and 2010). The specific methods used for data collection and analysis are discussed in Section 3.6.

3.4.3 Approach to Hybrid-decision support process (DSP) development

Chapter 2 introduced and discussed the literature on decision support and its use for organisational and strategic decision making. The importance of identifying the many influencing factors on the development of decision support was discussed in Section 2.2. These factors included the purpose of decision support, the context in which it is used, and the end-user requirements (Sutherland, 1983; Finlay, 1989; Turban *et al.*, 2007; Jakeman *et al.*, 2008b). In addition, the knowledge required to implement the new process, and hence the capabilities of the organisation should also be understood to ensure increased success of transfer and application (McIntosh *et al.*, 2008). These aspects of decision support design were incorporated during the development of the Hybrid-DSP. Guidance from Turban *et al.* (2007) was adapted for the Hybrid-Decision Support Process (DSP) development, and involved a seven stage process; i) problem identification, ii) identification of the purpose of the DSP, iii) identification of the design requirements for the DSP, iv) review of existing and potential methods for use as a DSP, v) design and development of the DSP, vi) application of the DSP, vii) assessment and integration of the DSP (Figure 3.4). These stages were progressively followed, with iterations and feedback through the stages of development as knowledge and understanding by the researcher and the organisation progressed, thus resulting in a combination of ‘top down’ and ‘bottom-up’ development of a Hybrid-DSP (as presented in Chapter 4). The information obtained through answering the research questions as part of the research and the stage in which it informed the development of the Hybrid-DSP is indicated within Table 3.2.

The purpose and design requirements of the Hybrid-DSP (Stages 1, 2 & 3), as well as the suitability of techniques, the overall design and the integration options of the Hybrid-DSP (Stage 4, 5 and 6) were progressively assessed during the research by the researcher in association with the reference group to reflect the organisational changes made during the research, (e.g. structural changes, a new investment planning system; development of WFD working groups) along with the changes resulting from implementation of the WFD (e.g. release of 25 EU Common Implementation Guidance [CIG] documents between 2003-2010, regional and national consultation periods for the development of Programmes of Measures [PoM] and River Basin Management Plans [RBMP] - draft and final for the Humber and Anglian regions). These influences occurred at various times during the research, although a significantly dynamic period between 2008-2009 is highlighted in Table 3.3 where multiple strategies and processes were developed alongside the introduction of new legislation.

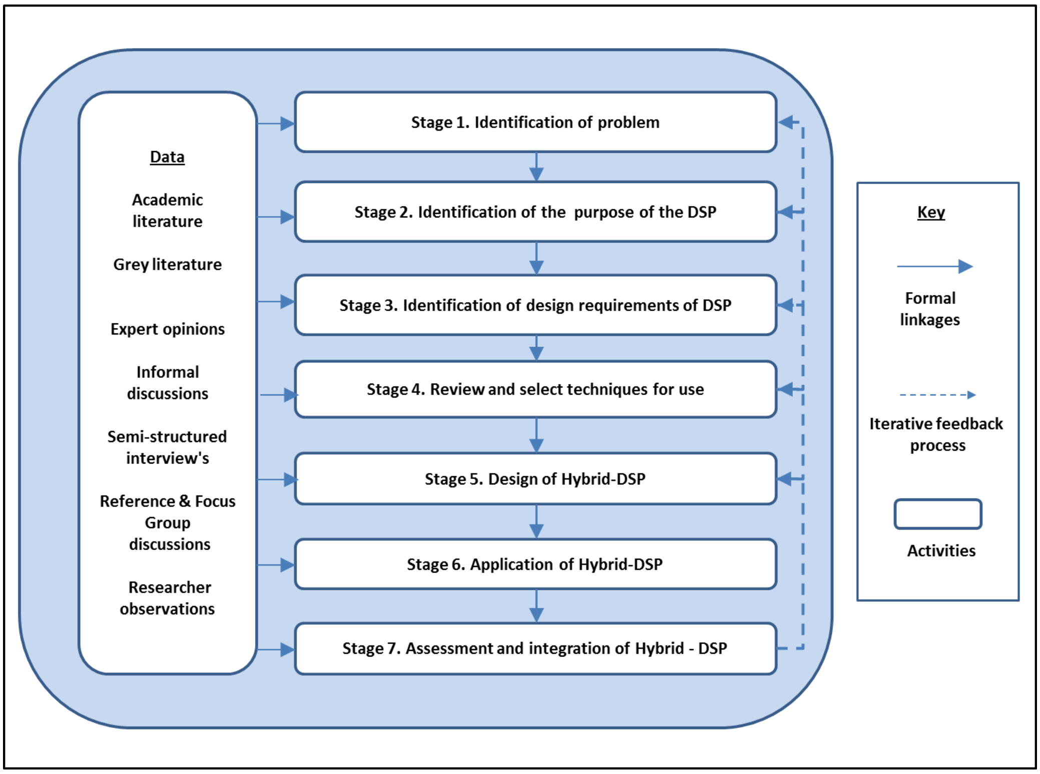


Figure 3.4: Hybrid-DSP development process (adapted from Turban *et al.*, 2008)

Table 3.2: Relationships between the research questions and the Hybrid-DSP development stages.

Hybrid-DSP Stages	Research questions								
	1.1	1.2	2.1	2.2	3.1	3.2	3.3	3.4	4.1
Stage 1			✓	✓					
Stage 2			✓	✓					
Stage 3					✓	✓			
Stage 4						✓			
Stage 5						✓	✓		
Stage 6						✓	✓		
Stage 7							✓	✓	✓

Table 3.3: Significant organisational and regulatory activities which influenced the research

		2006	2007				2008				2009				2010		
Type	***Significant documents/activities/event***	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Document (strategy)	AMP 5 (PR09)								Draft			Final					
Document (strategy)	Company Catchment Management strategy development								Draft			Final					
Software	Investment planning system: Asset Plus + implementation																
Process	Water company Drinking Water Safety Plan (DWSP) development																
Activity/Event	Diffuse pollution forum (DPF)																
Document (Strategy)	Strategic Direction Statement (SDS) (for 25 yrs) published																
Event	WFD Working Group Meetings (WFD WG) (AWS)						WFD WG	WFD WG	WFD WG		WFD WG						
Document (strategy)	RBMP development (Anglian and Humber)									Draft				Final			
Document	EC CIG documents (x25)																
Legislation	Nitrate Pollution Prevention Regulations																
Legislation	Water Supply (water quality) Regulations (amendments)																

Multiple sources of data were used over the period of the research to inform both the design of and content for the Hybrid-DSP which included; academic literature on decision support, legislative documents (e.g. WFD, CIS guidance documents), observations made by the researcher of organisational responses to WFD implementation, liaison with informants within the organisation and an assessment of organisational decision support processes within the case study organisation. These are further discussed in Section 3.6.1. As the WFD implementation proceeded and the details regarding the implications for potable water management and available data sources became clearer, the content within the Hybrid-DSP was adapted. For example, the Hybrid-DSP was revised to incorporate: new management actions (e.g. through the Programmes of Measures [PoM]), to tackle specific pollutants at both regional and site specific areas; relevant stakeholders associated with specific catchment areas; and the classification of groundwater 'status' levels which may influence potable water sources used in the future. These progressive developments led to revisions in the use and integration of the various elements of the Hybrid-DSP.

Groundwater contaminated with nitrate has been and continues to be a significant issue for the case study organisation, as well as for other water companies across the UK. In light of this, the problem of nitrate contamination in groundwater was selected as the focus for the development of the Hybrid-DSP, by the researcher in association with reference group members (see Section 3.8). Hence, the problem and influencing factors were investigated at both the a specific water source and at the strategic level.

The methods and techniques incorporated into the Hybrid-DSP were informed from the data obtained from the research context as well as from theoretical foundations. The combination of techniques are identified in Chapter 4 and include strategic assessment frameworks 'PESTEL' (Political, Economic, Social, Technological, Environmental and Legal) and 'SWOT' (Strengths, Weaknesses, Opportunities and Threats), resource and capability assessments as well as stakeholder analysis. Causal analysis techniques (DPSIR [Driving force, Pressure, State, Impact, Response], Bayesian networks) were also combined to inform further detailed descriptive, causal and probabilistic analysis at a site specific level. The theoretical basis from which the unique Hybrid-DSP has been developed therefore has the potential to be applied within a wider range of contexts, which is further discussed in Chapter 7.

3.5 Research methods and timescale

3.5.1 Qualitative and quantitative

The methods which are used for data collection and data analysis can be referred to as mono methods (one method for data collection and one method for analysis), multi-methods (multiple methods but only qualitative or quantitative), mixed methods (qualitative and quantitative) and mixed-model methods (use both quantitative and qualitative methods for both data collection and analysis) (Saunders *et al*., 2009). Using multiple and mixed methods which use both qualitative (using words) and quantitative data (using numbers) are common in management and organisational research, and provide a level of confidence in the findings produced.

Quantitative research is recognised to be useful to obtain and analyse data to prove or disprove hypotheses, although the context of the data may be lost; whereas qualitative data collection and analysis involves description and assessment of an holistic account of the research problem and its context (Denzin and Lincoln, 1998; Robson, 2002; Silverman, 2006). Creswell and Plano Clark (2009) recognise the distinctive characteristics of qualitative research as; i) being within the natural setting, ii) the researcher acting as the main research instrument, iii) an emergent research design and iv) the use of multiple sources of data. Through an inductive analytical process, patterns and categories are built from the data, and multiple views of the problem are considered (Creswell and Plano Clark, 2009). In the study of organisations, Cassell and Symon (2004) also contend that qualitative research methods are a recognised and valued research approach. Langley (2009) further supports the use of qualitative research methods for the conduct of research involving organisational processes. The disadvantages of undertaking such an approach, as Fish (1990) debates, are the extensive expenditure in time and money through the methods used to obtain data (note taking, collecting documents, transcribing, audio taping, and the researchers time immersed within the organisation).

However, having discussed the above, it should also be noted that the conversion between quantitative and qualitative data is sometimes feasible, especially within mixed-model research, where qualitative data can be 'quantified' (i.e. words to numbers), and quantitative data can be 'qualified' (i.e. numbers to words) (Saunders *et al.*, 2009).

The research philosophy of pragmatism, combined with a predominately inductive approach, and an applied research strategy within a case study organisation as discussed in Sections 3.2, 3.3 and 3.4, are suggestive of, and have informed the use of predominantly qualitative methods. The qualitative methods adopted, facilitated a time limited opportunity to discover and understand the complexities of the organisation's internal decision making processes (regarding potable water management and WFD implementation), and to inform the development of the Hybrid-DSP. A predominantly quantitative approach would have restricted the exploration of data, compromising the depth of insight and range of understanding. Thus, within the Hybrid-DSP which was designed as a process by which the implications of the WFD on the management of potable water supply could be understood and identified, quantitative methods of analysis were employed (e.g. descriptive statistics and the use of probabilities within Bayesian Network analysis).

Therefore throughout the research, although a predominantly qualitative approach was used to collect the data, a combination of qualitative and quantitative methods were used to analyse the data to inform i) the design of the Hybrid-DSP, ii) to provide data for inclusion in the Hybrid-DSP, and iii) to assess organisational responses to the Hybrid-DSP. The combined approach also increases the reliability in the data collected and the analysis conducted, through the use of multiple methods, and a combination of qualitative and quantitative analysis.

3.5.2 Timescale

The time period in which the research is undertaken has implications for the collection and analysis of data. Cross-sectional and longitudinal research approaches are commonly undertaken (Saunders *et al.*, 2009). Although, the context of the research was during a period of change in the water industry in the UK, and the implementation of a European Directive, the research was not focused on monitoring the changes or events within an organisation. Instead the focus was on the development of a Hybrid-DSP which could help manage the changes being presented within the external environment, and inform internal decisions regarding the management of potable water resources. Hence a cross-sectional approach was taken to the research.

3.6 Research methods for data collection and analysis

Within this Section the methods for data collection and data analysis in relation to each of the research questions are discussed. These methods include those used for i) the development of the Hybrid-DSP (its design and application) (which includes Research Objectives 1,2 and 3) and ii) organisational responses to its use (Research Objective 4). These are discussed in Section 3.6.1 and 3.6.2, and are summarised in Figure 3.5.

3.6.1 Data acquisition

Three main principles identified by Yin (2003) in the conduct of data collection for case study research involve the collection of data from multiple sources, the development of a case study database and the maintenance of a chain of evidence. Within qualitative research, the importance of understanding the nature of qualitative data, which require specific data collection approaches is highlighted by Denzin and Lincoln (1998). Conventional approaches for qualitative data collection include interviews, observations, document reviews as well as focus groups (Denzin and Lincoln, 1998; Robson, 2002; Cassell and Symon, 2004; Neuman, 2011). The strengths and weaknesses of these data collection approaches are presented in Table 3.4. The selection of the approaches, the relationship to the research questions, and the development of a case study database are discussed within this section.

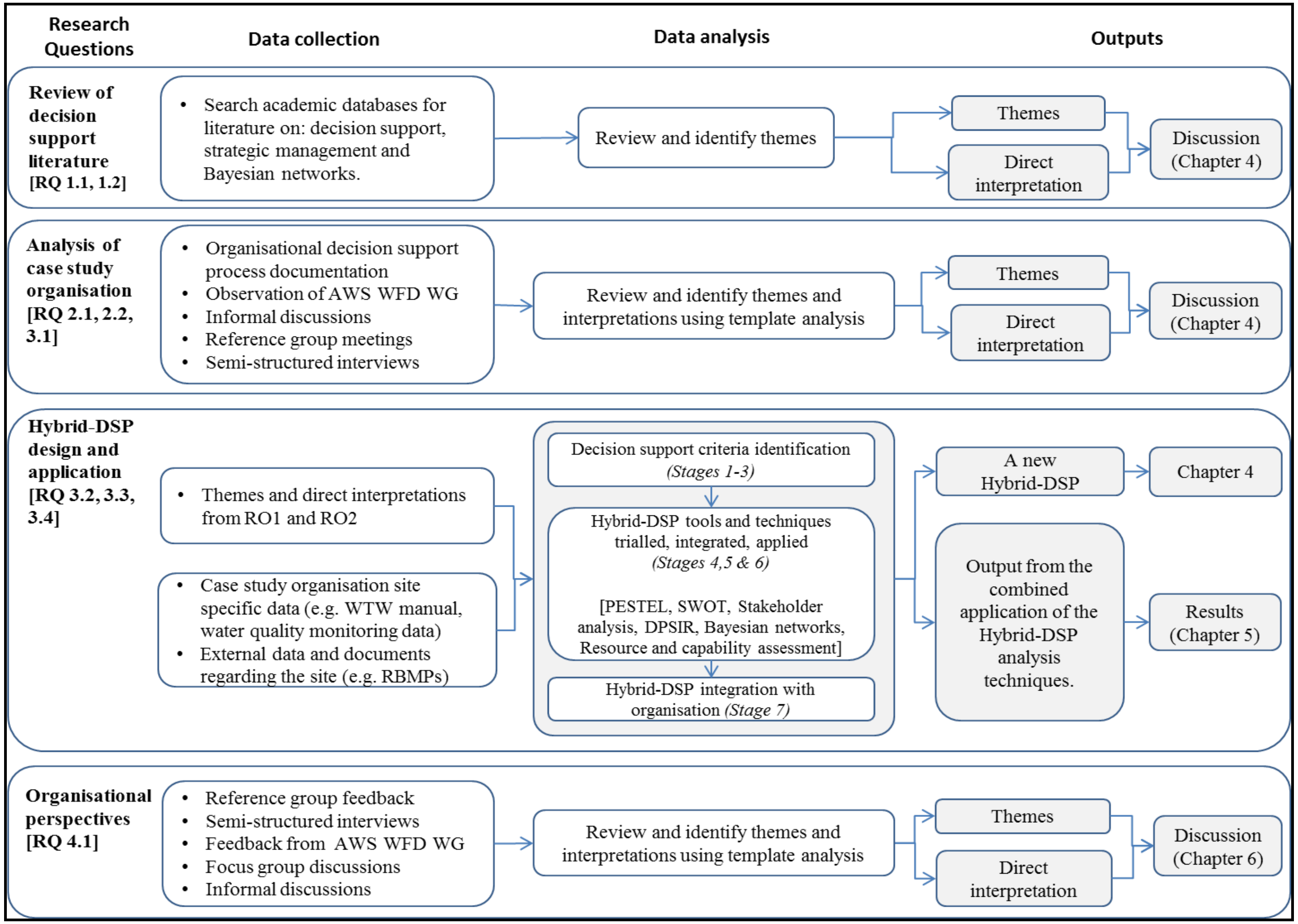


Figure 3.5: Overview of data collection and data analysis methods

Table 3.4: Strengths and weaknesses of data collection methods

Source of data	Strengths	Weaknesses
Documentation (e.g. meeting minutes/ agendas; organisational documents; grey literature)	Stable – can be reviewed repeatedly [1] Unobtrusive – not created as a result of the case study[1] Exact – contains exact names, references, and details of an event. [1] Broad coverage – long span of time, many events, and many settings. [1]	Retrievability – can be low[1] Biased selectivity, if collection is incomplete[1] Reporting bias – reflects (unknown bias of author[1] Access – may be deliberately blocked. [1]
Interviews	Targeted – focuses directly on case study topic[1] Insightful – provides perceived causal inferences[1]	Bias due to poorly constructed questions[1] Response bias[1] Inaccuracies due to poor recall[1] Reflexivity – interviewee gives what interviewer wants to hear[1]
Reference/ Focus groups	Natural setting allows people to express opinions/ideas freely [2] Open expression among group members of social groups who are marginalised is encouraged [2] People tend to feel empowered [2] Participants may query one another and explain their answers to one another [2] Quantity and range of data collection is increased from the responses of several people at the same time [3] Inexpensive and flexible method [3]	Only one or a few topics can be covered in a session [2] Focus groups may produce fewer ideas than interviews[2] Need to have an experienced facilitator for the group process [3] Conflicts may arise between personalities [3]
Direct Observations	Reality – covers events in real time[1] Contextual – covers context of event[1]	Time consuming[1] Selectivity – unless broad coverage[1] Reflexivity – event may proceed differently because it is being observed[1]
Participant observations	Insightful into interpersonal motives[1] Good at explaining ‘what is going on’ in particular social situations [4]. Useful for researchers working within organisations [4]	Bias due to investigators closeness/ manipulation of events[1] [4] Time consuming [4] Can present ‘role’ conflict for the research (colleague/ researcher) [4] Recording data is difficult [4]
Note: Sources include: [1] Yin, 2003:86, [2] Neuman, 2011; [3] Robson, 2002, [4] Saunders et al., 2009.		

During the research, a range of methods were used to collected data, which included: informal discussions, reference and focus group discussions, semi-structured interviews, documents (e.g. organisational reports and systems, legal documents), researcher observations, operational site visits. An overview of these methods, when they were used, and how they relate to the research questions is presented in Table 3.6. The specific data collection methods used for the design and application of the Hybrid-DSP, and the organisational responses are initially presented, followed by a discussion of each method in the subsequent paragraphs.

Data collection for the design and application of the Hybrid-DSP

Aspects of the collection of data to inform the design and application of the Hybrid-DSP have been mentioned in the previous paragraphs, and are now further detailed. In Section 3.4.3 Figure 3.4 presented the development stages of the Hybrid-DSP. The data collected to inform these stages was iterative, due to both the researcher and organisational understanding developed with regard to the impacts of the WFD on potable water management, and the requirements of the organisation for decision support. Therefore both primary and secondary data were collected cumulatively through multiple methods in response to the research questions (Table 3.6), and contributed to each of the stages of the Hybrid-DSP development and application (see Section 3.4.3, Table 3.2). Data used to design the Hybrid-DSP included the WFD, semi-structured interviews, observations, and internal organisational documents. Data used to apply the Hybrid-DSP included data from environmental legislation, case study organisational documents and databases, responses from interviews with participants, data from external organisations (e.g. regulators). Data from the same source were also used for both the design stages and to apply the Hybrid DSP (e.g. semi-structured interviews with case study organisation participants). An overview of which data collection activities were employed in the design and application of the Hybrid-DSP is provided in Table 3.5. The data was organised within both a Microsoft Excel® database and a database within the QSR NVivo software used for handling large data arrays (see also Section 3.6.2).

Table 3.5: Data collection methods to inform the stages of the Hybrid-DSP development

Data acquisition method	Hybrid-DSP Stages						
	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**Stage 7**
Reference Groups (RG)	✓	✓	✓	✓	✓	✓	✓
Focus Groups (FG)							✓
Semi-structured interviews (INT)	✓	✓	✓	✓	✓	✓	✓
Informal meetings/discussions (IM)	✓	✓	✓	✓	✓	✓	✓
Site visits (SV)						✓	
Observations of organisational mtgs	✓	✓	✓				✓
Academic literature				✓	✓	✓	✓
Documents from case study organisation	✓	✓	✓	✓	✓	✓	
External documentation: grey literature, academic, legal			✓	✓	✓	✓	
Organisational decision processes/systems	✓	✓	✓	✓	✓	✓	
Review of site specific documents			✓				

Data collection for organisational perspectives of the Hybrid-DSP

Data collected to inform organisational perspectives and responses to the Hybrid-DSP included discussions and observations made by the researcher in reference group and focus group meetings, as well as within the WFD Working Group (WFD WG) meetings (No.1 & No.4) (Table 3.7). Data was also obtained from semi-structured interviews and informal meetings with water managers. Hence, organisational responses were cumulatively obtained throughout the research period (Table 3.6), and reflected both the individual and combined methods used within the Hybrid-DSP.

Table 3.6: Overview of the data acquisition methods, when the data was acquired and relationship to the research questions

	2006	*2007*				*2008*				*2009*				*2010*			*Research Question*								
Data acquisition method	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	1.1	1.2	2.1	2.2	3.1	3.2	3.3	3.4	4.1
Reference Groups (RG)																			✓	✓	✓	✓	✓	✓	✓
Focus Groups (FG)																								✓	✓
Semi-structured interviews (INT)																			✓	✓	✓	✓	✓	✓	✓
Informal meetings/discussions (IM)																			✓	✓	✓	✓	✓	✓	✓
Site visits (SV)																					✓				
Observations of organisational mtgs																			✓	✓	✓				✓
Academic literature																	✓	✓			✓	✓	✓		
Documents from case study organisation																			✓	✓	✓	✓			
External documentation: grey literature, academic, legal																						✓		✓	✓
Organisational decision processes/systems																			✓	✓	✓	✓			
Review of site specific documents																					✓				

Note: Q = Quarters of the year

Use of Informants

In the conduct of qualitative research, the purpose of using informants from the study context provides a mechanism to identify insights which the researcher may not be able to see for themselves (Stake, 1995; Robson, 2002; Cassell and Symons, 2004; Creswell and Plano Clark, 2009; Neuman, 2011). Throughout the research, informants from within and external to the case study organisation provided contemporary evidence on the changes in the research context from their perspective. These discussions provided clarification of information and verification of data, through triangulation of information and observations made within the research. Purposeful sampling was employed at the start to identify informants, which led to snowball sampling as the research progressed (Robson, 2002). The names and roles of the informants who consented to be included in the study are listed in Appendix C together with the informants from outside the case study organisation who have all been allocated ID references. The ID references were necessary to maintain anonymity, as although it was made clear to all informants that the researcher was conducting research and therefore seeking information as part of this activity; consent to use company names, individual names or roles was not gained from all informants (e.g. opportunistic informants) (specific ethical considerations are further discussed in Section 3.7.3). Informants were engaged at various stages of the research, to a different extent dependent on their expertise and availability. The research activities and topics of discussion that each informant was involved in are noted within the case study database and the NVivo database (Section 3.6.2). Within the case study organisation 49 individuals were involved in and informed the research, supported by 33 individuals from nine different external organisations (Appendix C). These organisations included one academic institution, three consultancies, one software provider, three UK public bodies, and an additional UK water company. The job function of informants within the respective organisations ranged from senior management positions to operational maintenance personnel at specific WTW sites. Further information has also been gathered from external conferences and publicly advertised events where specific reference to named individuals is made within the research.

The focus of the informant discussions was centred on the impacts of the WFD on decision making and potable water management, either at the strategic level for asset investment, or at a site specific level. The informants within the reference group, semi-structured interviews, and focus group discussions were selected based on their experience and expertise in the fields of water resources management, environmental legislation implementation, asset management or decision support. In addition, informal discussions were conducted based on a naturalistic enquiry to understand the implications of development and deployment of the Hybrid-DSP. Personnel who were deemed not suitable for involvement in the study, included those who had no knowledge of the subject of the research topics, and those who were not able to correspond with the researcher within the time period or location of the research.

Reference Groups

Reference Group discussions provided an environment for knowledge sharing and exploration of issues related to the research context. Within the reference group the researcher adopted a facilitator role to allow for information exchange and application of techniques to develop the Hybrid-DSP, as discussed in Section 3.7.1. The reference group was comprised of five case study organisation participants and an academic expert, together with additional group members at different periods in the research for expert input. An organogram of the reference group members from the case study company is presented in Figure 3.6. Fields of expertise represented through the reference group members included: potable water strategic investment; water resources; potable water quality requirements; and environment legislation (e.g. WFD) within the case study organisation.

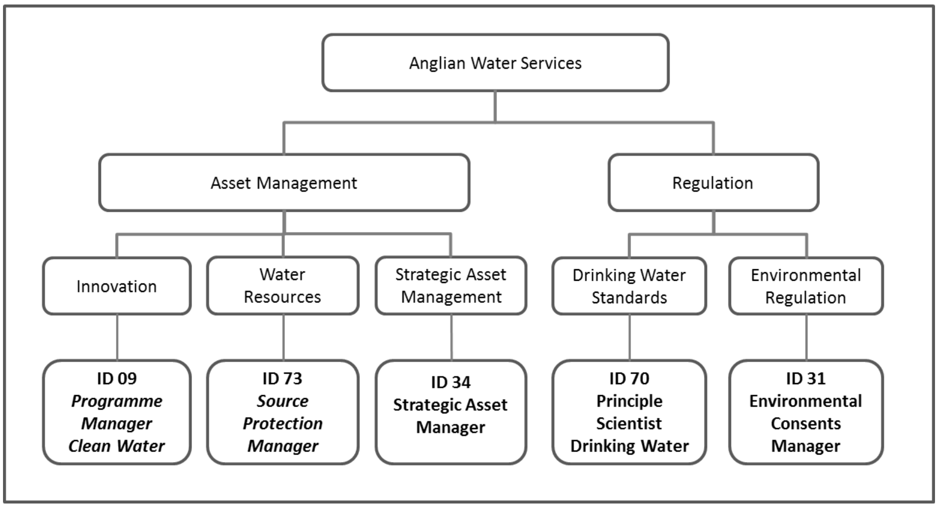


Figure 3.6: Organogram of central reference group participants within the case study organisation

Nine formal reference group (RG) meetings were held, with an average duration of two and a half hours (Table 3.7). This allowed for the Hybrid-DSP to be developed both within the reference group, and between meetings with individual informants, followed by further developments being fed back to the reference group for discussion.

Focus Group

Focus groups were used to specifically discuss the integration of the Hybrid-DSP during three half-day sessions (rows "FG1, 2 &3" in Table 3.7). The focus group included senior organisational representatives involved in investment planning (ID09, ID20, ID34, ID59, ID70, ID73, ID82) together with external asset management consultants (ID39, ID 45) who were involved in the development of the new organisational investment management process Asset Plus+. During the focus group session, the researcher adopted the role of facilitator; sharing information about the Hybrid-DSP with the participants, whilst also eliciting information to inform how the Hybrid-DSP would integrate into the organisation, and obtaining the perspectives of the water managers and consultants on the use of the Hybrid-DSP.

Table 3.7: Summary of all informants involved in the RG, WFD WG, and FG meetings and interviews between 2006-2010

			Informant ID reference number																									Total No. IDs
Research reference	**Dur (hrs)**	**Date**	**ID 34**	**ID 70**	**ID 73**	**ID 31**	**ID 9**	**ID 64**	**ID 77**	**ID 33**	**ID 22**	**ID 76**	**ID 20**	**ID 82**	**ID 59**	**ID 16**	**ID 10**	**ID 35**	**ID 79**	**ID 81**	**ID 66**	**ID 25**	**ID 80**	**ID 45**	**ID 39**	**ID 19**	**ID 21**	
RG1	2	03/10/2006	✓	-	✓	-	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		6
RG2	2	11/01/2007	×	-	×	-	✓	×	-	-	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		3
RG3	2	12/02/2008	×	✓	✓	✓	✓	×	-	✓	-	-	-	-	-	-	-	-	-	-	×	-	-	-	-	-		5
WFD WG 1	2.5	03/03/2008	-	✓	✓	✓	-	✓	×	✓	-	✓	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	-		9*
RG4	3	15/05/2008	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		6
WGD WG 2	2.5	27/05/2008	-	✓	✓	✓	-	-	-	×	-	×	-	-	-	✓	✓	✓	-	-	-	-	-	-	-	-	✓	7*
RG5	3	13/08/2008	×	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		5
INT 1**	2	26/08/2008	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓		2
WFD WG3	2.5	27/08/2008	-	×	×	✓	-	-	×	✓	-	✓	-	-	-	✓	✓	×	-	-	-	-	-	-	-	-		5*
INT 2	2	02/09/2008	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
INT 3	2	04/09/2008	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
INT 4	2	04/09/2008	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
RG6	3	19/12/2008	×	✓	✓	✓	✓	-	-	-	-	✓	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		6
WFD WG4	2	13/03/2009	-	✓	✓	✓	-	-	-	×	-	-	-	-	-	×	✓	-	✓	✓	-	-	-	-	-	-		6*
RG7	3	23/04/2009	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-		6
RG8	2	26/08/2009	✓	×	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-		6
INT 5**	2.5	09/09/2009	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		2
INT 6	2	12/09/2009	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
INT 7	2	22/09/2009	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
INT 8	2	23/09/2009	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		1
FG1	2	03/11/2009	✓	-	-	-	-	-	-	-	-	-	✓	-	✓	-	-	-	-	-	-	-	-	-	-	-		3
FG2	4	03/11/2009	✓	-	-	-	-	-	-	-	-	-	✓	✓	×	-	-	-	-	-	-	-	-	✓	✓	-		5
RG9	2.5	06/01/2010	✓	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	-	-	-		8
FG3	2.5	23/02/2010	✓	✓	✓	×	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		4
Total RG attended			5	6	8	7	9	1	1	1	1	1	-	-	-	-	-	-	-	-	8	2	1	-	-	-	-	
Total FG attended			3	-	-	-	-	-	-	-	-	-	2	2	1	-	-	-	-	-	-	-	-	1	1	-	-	
Total WFD WG attended			-	3	3	4	-	1	-	2	-	2	-	-	-	3	4	2	1	1	-	-	-	-	-	-	1	
Total No. of Interviews			2	2	2	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	

Note: Dur = Duration of meeting/ interview in hours, RG = Reference Group, WFD WG = Case study organisation WFD Working Group, FG = Focus group. Presentations were given by the researcher at all RGs (except RG1), all FGs and at WFD WG1 and 4. ID64 left the water company in 2008. ID77 role changed in 2007 and was no longer part of the RG. * indicates additional members of the case study organisation were present although not directly part of the research. ** = indicates a joint interview. [Key: ✓ = present, × = absent, - = not required to attend.]

Semi-structured interviews

Semi-structured interviews were conducted during the research for the purposes of identifying the features to be incorporated into the design and application of the Hybrid-DSP, eliciting data for the tools and techniques used within the Hybrid-DSP and to assess individual and corporate responses to the use of BNs and the Hybrid-DSP. The time consuming nature of interviews, through their preparation and logistical arrangements with participants, the high levels of concentration required by the researcher in conducting the interviews, the time available by the participants to take part in the process, and the potential for data-overload due to the detailed data gathered are widely documented in the field of qualitative research (Denzin and Lincoln, 1998; Robson, 2002; Silverman, 2006; Neuman, 2011). Despite the potential of alternative methods of data collection (e.g. email questionnaire, or a focus group or workshop), semi-structured interviews offered a more individual and detailed account to be obtained, where interview participants were able to clarify their thoughts on the issues being explored. These attributes have been recognised by King (2004a) and Silverman (2006). Furthermore, personal views were able to be expressed without other group members being domineering. A structured interview approach, would not have allowed for exploration of issues and perspectives identified by the participant, and consequently would limit the detail captured during the interview process.

'Semi-structured', 'un-structured', 'depth' or 'exploratory', interviews all have the same purpose; to understand the issue or topic from the participants' perspective (King, 2004a). The protocol, as recognised by King (2004a) and Creswell and Plano Clark (2009), for the design and implementation of such interviews includes: i) definition of the research question and questions to be answered through the interview ii) creation of the interview guide, iii) selection and recruitment of participants, and iv) conducting the interviews (the interview guides are presented within Appendix D). The interview guide included pre-identified questions, which were followed up with questions dependent on the participants responses to the questions and their level of experience and knowledge related to specific topics (e.g. investment planning). The interview agenda was developed based on prior discussions and engagement with the case study organisation, and observations made by the researcher in relation to the use of existing methods used within the case study organisation. Information was collected from participants through two separate interview phases. Each phase related to the use of a specific method to understand the implications of the WFD for the management of water resources. During September 2008, the initial phase of the interviews were conducted to explore the use of a strategic screening framework and the use of a stakeholder analysis method (introduced within Reference Group meeting No.5 [Table 3.7]). A second phase of interviews focused on assessing the capabilities of the organisational investment decision making processes, the identification of and inclusion of WFD impacts on investments and the clarification of design and evaluation criteria for the Hybrid-DSP. The two phases allowed for further information to inform the design and organisational implementation of the Hybrid-DSP, whilst also providing perspectives of the use of the methods within the Hybrid-DSP.

The interview participants required knowledge of both the research being undertaken and the tools and techniques being used. Therefore the interview participants were selected from the reference group due their prior involvement in the research study. The participants themselves were also considered to be representative of the potential end-users of the Hybrid-DSP and their engagement in its design and use would contribute towards the development of organisational capability to implement the Hybrid-DSP. The organisational perspectives represented by the interview cohort included; the water resources department, drinking water quality team, environmental regulation team, clean water innovation team, and the strategic asset management team. These multiple perspectives provided an opportunity for the researcher to understand the level of knowledge across the organisation with regard to the WFD implementation and the ability of the participants to use the techniques as part of the Hybrid-DSP. Due to availability constraints joint interviews were undertaken in only two instances.

The data collected for each of the RG, FG, WFD WG, and semi-structured interviews included field notes, observations made by the researcher, digital voice recordings and full transcripts for each recorded interview. The recordings and full transcripts of interviews provide a “highly reliable” source of data (Robson, 2002), in association with observations and notes made during the interviews. Although complete digital voice recordings of the interviews and informal discussions were intended, they were not made due to a number of reasons. Firstly, during early discussions with informants within the case study organisation (e.g. reference group participants) nurturing an open and trusting relationship with the informants was considered important to gain both an understanding of the organisation and of the context of the research. Secondly, the researcher wanted to allow the focus of the research to develop, and therefore narrow the nature of the data to be collected. Audio recordings of early discussions would have resulted in a vast amount of detailed data to be analysed which would have been poorly focused on the central concerns of the research. Thirdly, due to the applied nature of the research, maintaining momentum on developing issues within the research setting meant the researcher was not always able to record discussions, due to the various settings and locations in which they took place (e.g. discussions in public locations: conferences, restaurants, on site outdoors near noisy machinery, on training courses [e.g. organisational training events and software specific training], at team meetings).

The adoption of a less formal approach during the initial period of the research allowed for any politically sensitive mis-understandings of information, or potentially confusing contributions (due to the limited knowledge of informants) to be handled pragmatically. As the research developed, and organisational knowledge increased, the conduct of the semi-structured interviews allowed for formal audio recordings to be made with full transcripts for analysis. Six out of the eight interviews were transcribed, with an average length of two hours each. Extensive notes were made for all interviews, and formed the basis for analysis of the two interviews not transcribed. RG 5 was also audio recorded to capture details concerning the use of the Stakeholder Analysis exercise, although not transcribed directly, but detailed notes were made from the recording. This was to obtain details of the discussions between the participants regarding the nature of the influence and interest of identified stakeholders, and how they relate to the WFD impact on potable water management. FG 1 and FG 2 were also audio recorded to document the discussions between the participants regarding the integration of the Hybrid-DSP with the organisation and transcribed. These were specifically recorded due to the involvement of external consultants within the focus group, and the limited time for the researcher to make detailed notes whilst facilitating the discussion. During informal discussions and the semi-structured interviews, the researcher used active listening to re-state and paraphrase what the interviewee said, to confirm researcher understanding and interpretation, to increase the accuracy of the information obtained. Interpretations from both phases of interviews were fed back to the case study organisation via the reference group meetings, where participants were able to clarify perspectives on the use of the techniques, and discuss their function within the Hybrid-DSP. Further design issues and information was elicited progressively from the reference group meetings, which contributed to the development of the Hybrid-DSP.

Documentary data

Documentation external to, and from within the case study organisation has been used within this research. These various sources of documents provided information in order to answer the research questions, and subsequently informed the design and application of the Hybrid-DSP. Internal documentation was collected through accessing the water company systems and databases, whilst external data was obtained through the development of an understanding of the research context and decision support applications within the water sector. A wide range of different types of 'external' documentation was collected and used within the research to inform the design and application of the Hybrid-DSP which included; academic journals, European legislation, regulatory reports, industry reports/ articles, and websites. The documents of specific interest included the WFD (2000/60/EC), the RBMPs (EA, 2009a; EA, 2009b), and organisational specific documentation related to internal systems and processes used for potable water management.

Observations

Observation as a qualitative method is recognised as appropriate by Silverman (2006) for the conduct of exploratory studies. Although observation involves a subjective interpretation made by the researcher, it is the preferred method to understand culture and organisational dynamics (Stake, 1995; Silverman, 2006; Robson, 2002; Cassell and Symons, 2004). This technique of data collection allowed the researcher to obtain an understanding of organisational awareness and comprehension of the WFD and how it is being incorporated within organisational decision processes (RQ 2.2) as well as an understanding of the research context within the case study organisation. These observations contributed to the design of the Hybrid-DSP, and to identify in what way it could be implemented within the water company (RQ 3.1-3.4). In addition observations were made of the RG and FG participants and those who participated in semi-structured interviews with regard to their responses to the use of the techniques within the Hybrid-DSP (RQ 4.1). Observations by the researcher were also made during informal and formal meetings and included four specific WFD Working Group (WFD WG) meetings. The specific WFD WG, which was established during 2005, consisted of senior members of the organisation from six departments (asset management, customer services, regulation, water services, wastewater, and human resources). The purpose of the group was to understand and respond to the implementation of the WFD and hence address any specific regulatory requirements. In the 'participant as observer' role adopted during these meetings some participation was required (e.g. presentations of research ambitions and findings) whilst also observing. These meetings took place on the 3rd March 2008, 27th May 2008, 27th August, 2008, 13th March 2009. The last meeting scheduled for the 11th July 2009 was cancelled, and the WFD WG was disbanded, in response to the closure of consultation on the development of the RBMPs in June 2009.

Site Visits

Site specific observations and field notes were made when visiting operational WTWs, and surveying and photographing the local area within the groundwater catchment (EA defined Source Protection Zones 1, 2 and 3). These notes were made concerning potable water treatment processes and site details to provide data to inform the design and application of the Hybrid-DSP. Informal discussions with operational staff and photos of catchments and land use activities surrounding groundwater sources provided evidence about operational risks posed by the physical environment (e.g. manure heaps on land within the Source Protection Zone [SPZ]). The site visits also provided specific details regarding the physical context which the implementation of the WFD and potential management actions were to target. This primary data collected provided contextual information to inform the specific variables and the relationships between variables within the Hybrid-DSP.

A database of the information collected during the research was generated using Microsoft Excel® as an indexing tool, combined with QSR NVivo 9, to store the documentation for analysis. The database incorporated all reference materials, including summaries of the documents used, field notes, memos, and digital recording transcripts. All activities, events and documents were indexed to allow for instant access and retrieval of information. The referencing system helped identify chains of evidence to linking the research purpose through to research questions and relevant data sources. A summary of all the data collection methods and the respective nature of the data collected is presented in Table 3.8.

Table 3.8: Summary of data acquisition methods, references, data type, number of data events/activities

Data collection method	**Method Reference**	**Data type**	**Number**	**Description and purpose**
Reference groups	Robson (2002); Steyaert and Bouwen (2004)	Text	9 meetings	Reference group used to provide a consistent group of water managers to provide data and participate in the development of the Hybrid-DSP. (memos, agendas, minutes, audio recordings)
Focus groups	Robson (2002); Steyaert and Bouwen (2004)	Text	3 meetings	Focus groups used to provide detailed information on the integration of the Hybrid-DSP with internal asset management system (Asset Plus+) and integration of the Hybrid-DSP within the business units across the organisation. (memos, agendas, minutes, audio recordings)
Semi-structured interviews	Robson (2002); King (2004a)	Text & audio	8 interviews	Four held in September 2008, and four in Sept 2009.
Informal discussions	Robson (2002)	Text (memos)	61 (dis) with 82 (inf).	Discussions (dis) with informants (inf) took place between 2006 and 2010 concerned with specific information related to internal organisational decision processes and systems, provision of data for inclusion in the Hybrid-DSP, and to provide perspectives on the use of the Hybrid-DSP.
Site Visits	Robson (2002), Yin (2003)	Text, graphics, numerical	9 sites	Sites within AWS included: Elsham WTW, Marham WTW, Clapham WTW, Cotton Valley WWTW, Barrow WTW and the associated boreholes at Thornton, Barton and Goxhill and a site visit to the Dene Catchment within Wessex Water (photos, maps, field notes)
Participant observation	Adler and Adler, (1998), Robson (2002), Waddington (2004), Neuman (2011);	Text	4 meetings	Four AWS WFD WG** meetings (Dates: 03/03/2008, 27/05/2008, 27/08/2008, 13/03/2009) and a Diffuse Pollution Forum (24th March 2009). General observations were made at all informant meetings, interviews, as well as reference and focus groups.
literature on DSS/strategic management/BNs	Robson (2002)	Text	>500 articles	Academic articles on DSS, Strategic management methods, BNs.
Documents: from case study organisation	Robson (2002), Yin (2003)	Text	>100 documents	Iterative – for specific data required
Documents: grey literature, reports, legal.	Robson (2002);	Text	>100 documents	Iterative over 4 years, including the WFD, GWD, DWD, Nitrates directive, (published documents – grey literature/ reports/ legal)
Organisational decision processes/systems	Robson (2002)	Text/ numerical	3 systems	ARTS 2000, Crystal QD warehouse: use and notes on data management. Asset Plus + system: observation of its use to inform Hybrid-DSP integration options.
Site specific data from case study organisation	Robson (2002), Yin (2003)	Text/ numerical	5 main sources	Crystal QD warehouse, Arts 2000, DWSP, Asset Plus +. Iterative collection of data to inform specific variables within the Hybrid-DSP.

3.6.2 Data analysis and interpretation

The purpose of data analysis is to attribute sense and meaning to the data collected. To achieve this the process of data analysis involves; the preparation of the data for analysis, the conduct of different types of analysis, generating an understanding of the data, presenting the data and making an assertion or interpretation of the data within its wider context (Cresswell and Plano Clark, 2009). The generation of meaning from the data, can be conducted as distinct activities, or as an on-going process of attributing meaning to first impressions which are developed into a final account. Methodologically, the conduct of qualitative data analysis is considered by Johnson and Harris (2009) to have few standardised approaches. Further to this Johnson and Harris also identify that specific types of data (e.g. documents) do not relate directly to a standard type of analysis, as generally understood for quantitative studies. The large quantity of data of various types recognised by Stake (1995) to be collected through qualitative research has a direct impact on the data analysis technique selected. The argument here is that because data in its entirety will typically not be analysed, only significant sources of data with the greatest quality should be subjected to detailed analysis. Specific techniques for the analysis of qualitative data include template and matrix analysis as well as direct interpretations, which can involve the use of text analysis software (e.g. QSR NVivo [Bazeley 2007]) qualitative data displays, time series, logic models (Denzin and Lincoln, 1998; Robson 2002; King, 2004b, Neuman 2011). The determination of the appropriate analysis method is directly related to the nature of the research questions of the study. Research questions can provide the ‘template’ for the analysis of the data, and the nature of the patterns to be identified, or patterns can emerge unexpectedly from the analysis of the data. Codes may be listed to show frequencies, or variation between interviewees’, patterns between codes could be used in relation to certain subjects or issues, although the frequency of codes alone does not have any meaning without the respective contexts.

During this study, to answer the predominantly ‘How’ and ‘What’ research questions, and hence the research objectives, direct interpretation and template analysis were selected to analyse the qualitative data collected (as summarised in Figure 3.5, and discussed in Section 3.6.1). The software QSR NVivo 9 was used to manage and analyse the data.

Template analysis

The presentation of findings from template analysis do not follow a universal format. Generally the approach taken is to summarise detailed notes, and illustrate key findings or assertions with quotes or paraphrases to produce a coherent story and build an understanding of the phenomenon (King, 2004b; Saunders *et al*., 2009). Findings are presented as: individual case studies (differences/ similarities between cases e.g. different perspectives); an account structured around the main themes (e.g. illustrative examples from transcripts, experiences which highlight main themes); or thematic presentation of findings (e.g. different documents to illustrate main themes). The strength of using a template approach for the analysis is the flexible approach it offers, which is applicable for a wide range of studies. It is also useful to examine different perspectives, whilst facilitating the establishment of themes, patterns and categories. However, in using this approach, measures should be taken to ensure templates do not become overly complex, unmanageable, and descriptive. In due course, using a template can provide for a structured approach to the management of the data, to result in a clear and organised report. Although King (2004b) recognises the benefits of the approach, it is still an emerging technique (Matheus, 2009).

Using template analysis themes were identified to inform the research questions. In addition, techniques for data analysis within the Hybrid-DSP were also selected based on the analysis conducted during RQ 1.1, 1.2, 2.1 and 2.2, as well as further feedback from analysis of data collected to inform RQ 4.1. These included PESTEL, SWOT, systems analysis of the potable water supply chain, stakeholder analysis, resource and capability analysis, and Bayesian networks. (The application of Bayesian networks involved the use of a specific software package 'Hugin A/S Expert' for which the researcher undertook specific training provided by the software supplier between 2-4th December 2008). How the techniques were used (and the associated research questions) to inform each of the Stages 1-7 of the Hybrid-DSP development are summarised in Table 3.9 (see Figure 3.4 in Section 3.4.3).

Table 3.9: Relationship between data analysis methods, stages of the Hybrid-DSP development, and research questions

Stages of Hybrid-DSP development		RQs addressed	Data analysis methods		
			Direct interpretation	Template analysis	PESTEL, SWOT, Stakeholder analysis, BNs, system analysis, resource and capability analysis
Stage 1	Identify problem	RQ 2.1, 2.2	✓		
Stage 2	Purpose of Hybrid-DSP	RQ 2.1, 2.2	✓		
Stage 3	Design requirements	RQ 3.1	✓	✓	
Stage 4	Review and select techniques	RQ 3.2	✓	✓	✓
Stage 5	Design of Hybrid-DSP	RQ 3.2, 3.3	✓	✓	✓
Stage 6	Apply Hybrid-DSP	RQ 3.2, 3.3	✓	✓	✓
Stage 7	Assess and integrate Hybrid-DSP	RQ 3.3, 3.1, 4.1	✓	✓	

Note: RQs are those which are directly addressed in the stage of the Hybrid-DSP, whilst the RQs in [ ] identify those RQs which support/ inform the stage in the development of the Hybrid-DSP.

Direct interpretation and thematic analysis was used within the research to understand the developments within the literature related to the emerging technique of Bayesian networks for decision support in water resources management (RQ 1.1, 1.2). Direct quotes from interviews, observations, and documents were used as evidence to support the identification of criteria to be included within the design of the Hybrid-DSP, whilst also providing a basis for a thematic and matrix analysis of the multiple themes identified from the different informants (RQ 2.1, 2.2, 3.1). The use of direct interpretations from legal documents, and operational manuals were used to provide direct data for inclusion within the Hybrid-DSP application (RQ 3.2, 3.3, 3.4). Whilst further direct interpretation from interviews, focus group discussions provided evidence for the implementation and integration requirements of the Hybrid-DSP. Organisational responses to the Hybrid-DSP and its techniques were obtained using direct interpretation from interviews and observational notes, whilst also providing for thematic and matrix analysis to inform the responses.

Direct interpretation as a technique was applied where data was directly taken from the source (e.g. paragraphs from the WFD, quotes from interviews). A direct interpretation approach was appropriate due to the high quality of the data sources which could be used directly as evidence in the development of the arguments presented within the thesis.

Template analysis was used to code segments of text from multiple sources of data (academic literature, semi-structured interview transcripts, organisational documentation, observations, meeting minutes) using the software QSR NVivo 9. The codes included 'a priori' codes identified through the research questions, the academic literature, and the specific categories (hence codes) required for specific techniques used within the Hybrid-DSP; in combination with emergent codes from the data. The codes used in the template analysis, were aggregated to create themes, which provided an understanding of the organisational responses to the use of the Hybrid-DSP and the individual techniques. Thematic analysis as a technique is recognised as a technique for the identification of themes from textual data sources (Braun and Clarke, 2006) and have been used previously in the water sector for research (e.g. Spiller *et al.*, 2009; Marlow *et al.*, 2010). The use of template analysis provided a mechanism to analyse large quantities of textual data which required analysis both within the document, and across multiple data sources. Quantitative analysis of word frequencies and discourse was not conducted due to the focus of the study being on the process of decision support and organisational responses to the WFD implementation, not on the detailed analysis of specific word references.

Analysis of the literature relating to decision support (RQ 1.1, 1.2) was conducted using template analysis as well as direct interpretation. This allowed for direct issues to be incorporated into the analysis, whilst further themes related to the development of decision support and Bayesian network application were identified through a template analysis. For example, issues identified through template analysis included, the role of participation in decision support development using BNs. Although software was not used to conduct the review of the academic literature, the themes identified were used to inform the development of the Hybrid-DSP, and are presented in the discussion within Chapter 4.

The analysis of the organisational responses to the Hybrid-DSP RQ 4.1 was conducted through the analysis of case study organisational documents, informal discussions, reference and focus groups, semi-structured interviews, participant observation of AWS WFD meetings and general observations made by the researcher. The data was analysed through both direct interpretation, and through template analysis, to understand the implications of the Hybrid-DSP on the organisation and its ability to respond to the implementation of the WFD. The findings from the template analysis are presented within the discussion within Chapters 4, 5 and 6.

During the analysis the same data source (e.g. semi-structured interviews) provided evidence to answer multiple research questions (e.g. [RQ 2.1, RQ 2.2] to understand current organisational decision processes for potable water management, [RQ 3.1, RQ 3.2] to inform the design of the DSP, and [RQ 4.1] to identify responses and perspectives of the participants use of the Hybrid-DSP.

The overall process used to analyse the qualitative data, followed six steps influenced by Cresswell and Plano Clark (2009). These involved 1) the organisation and preparation of data for analysis, 2) familiarisation with the data, 3) further analysis through coding of data, 4) the development of themes from the data, 5) display findings of the analysis, 6) the interpretation of the data and findings through a report (Figure 3.7). The data collected through the case study was analysed iteratively through multiple coding, reading and interpretation. The codes used were both emergent from the data and based on ‘a priori’ codes associated with the frameworks used within the Hybrid-DSP (e.g. political, economic, social, technical, environmental, legal [for the PESTEL analysis], strengths, weaknesses, threats, opportunities [for the SWOT analysis of the organisations decision support processes for potable water management]) to categorise the “factors” (See Chapter 4).

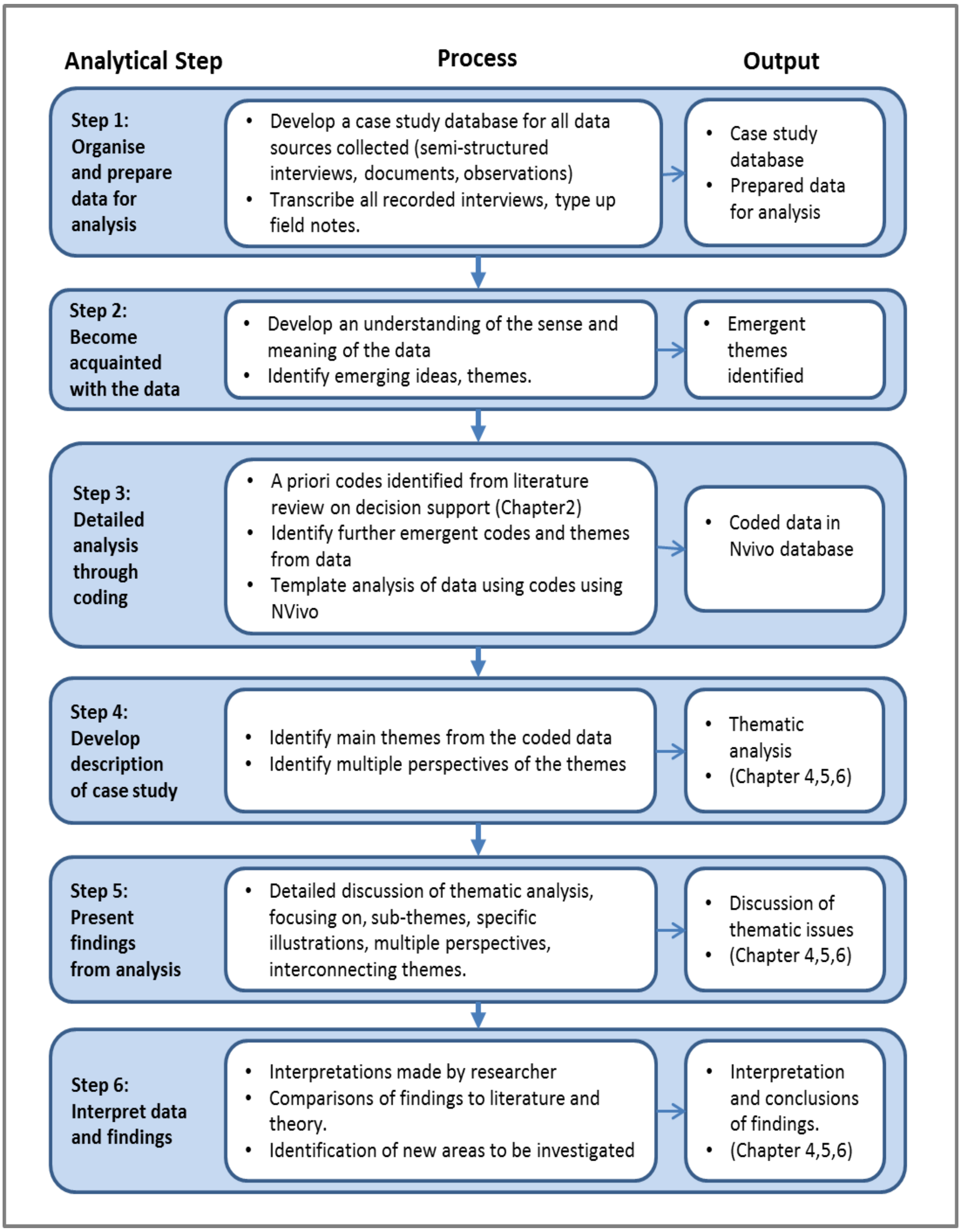


Figure 3.7: Overview of general approach to data analysis (adapted from Creswell and Plano Clark, 2009)

3.7 Research quality

3.7.1 Role of researcher

Throughout the research a \`symbiotic link\` between the researcher and the researched was established which led to a \`partnership approach\`, recognised by Robson (2002) as applicable for applied research. A partnership approach with members of the case study organisation was critical to understanding the organisational decision making processes in response to the implementation of the WFD. Stake (1995) recognises that the researcher can take on many roles from teacher, participant observer, interviewer, reader, story teller, advocate, artist, counsellor, evaluator, consultant, as well as others. The emphasis of which roles to adopt were continuously reviewed by the researcher, dependent on the context of the situation, and the research activities being carried out. Creswell and Plano Clark (2009) outline the main issues to consider in the role of the researcher as: the provision of enough background information to allow the participants to understand and interpret the phenomenon of interest in the study; identify the connections between the researcher and the participants; identify permissions sought for access to information within the study and identify the ethical issues which may arise from the research. Throughout the study, the researcher adopted the role of '*facilitator*' (Saunders *et al*., 2009) initially to inform the organisation in relation to the WFD implications for the management of potable water, whilst also informing the organisation of the various techniques considered in the development of the Hybrid-DSP. This approach provided an opportunity for the researcher to inform the participants regarding the research contextual knowledge (e.g. regarding the WFD) to enable further exploration of the WFD and the potential Hybrid-DSP techniques in a participatory way.

Access to information was identified and agreed at the start of the research, where training courses were provided by the organisation on the use of the internal databases and systems (e.g. Crystal QD warehouse, ARTS 2000). Further access to documents, personnel and other business processes (e.g. Risk and value, Asset Plus) were also facilitated through the research through liaison with organisational personnel. At all times the researcher was introduced as a researcher and the nature of the research explained.

Through the partnership, the researcher adopted the role of a '*sensitive enquirer'*, as recognised by Robson (2002), which involved having an open mind and the ability to use and respond to unexpected and opportunistic information throughout the research. Whilst Robson identifies the role of '*sensitive enquirer'*, he also identifies the role of '*researcher as instrument'* as applicable for conducting social research where the researcher predominantly collects information. The researcher consequently makes interpretations based on the researchers perspective. Throughout this research, the '*researcher as instrument'* was adopted for situations where information was obtained from observations (e.g. meetings, site visits, organisational systems and operations). The development of the Hybrid-DSP also involved engagement with the informants to identify key variables and data sources, whilst also trialling the methods. Turban *et al*., (2007) writing from the perspective of decision support, identify the role of the researcher as a '*knowledge engineer'*, where the elicitation of information and knowledge from the research participant is conducted, to inform the development of decision support. The role of '*knowledge engineer'* is commonly referred to within the fields of decision support system development, but was adopted for the purposes of the research as a complementary approach to the '*researcher as instrument'*. During the research, the researcher therefore embraced various roles for different research purposes which is consistent with the nature of flexible research.

Throughout the research the researcher was able to draw upon three years of prior professional experience in an advisory role to water managers on the impact of European environmental legislation on water company operations. This was obtained with a different UK water and wastewater company and hence provided prior contextual insights which enabled the researcher to further understand and interpret the issues associated with the implementation of the EU WFD (2000/60/EC) within the specific case study company in this research. This experience also enabled the researcher to adapt to the many organisational and contextual changes presented during the research.

Trust and integrity of the researcher was created through the engagement in an open and honest relationship, where discussions were held with informants to understand the issues from their perspective, whilst the researcher was able to draw upon previous experience and literature sources to offer evidence based insight and context to issues arising. The nature of the relationship was reinforced through the frequent presence of the researcher within the case study organisation and liaison with multiple personnel from numerous business units. This allowed developing issues, requirements and uncertainties regarding the management of potable water resources and the implementation of the WFD to be identified, and discussed openly with key informants within the organisation. Presentation of evidence is one of the main factors which influences the level of trust in the researcher. Within the research, evidence of the implications of the WFD for the organisation and the information used during the development of the Hybrid-DSP was presented to informants through reference group meetings and on a one to one basis. Engagement with the research participants permitted information sharing, and involvement in how the research developed and how the organisation might respond to the WFD. The use of first-hand information obtained from the key informants provided a sense of immediacy and intimacy about the nature of the research.

The potential for researcher bias due to prior experience in the industrial context was identified and mechanisms were implemented to reduce its influence. These included; openness, transparency, and objectivity during the development of the research with the informants and participants within the organisation. Triangulation of multiple methods of data collection further reduced researcher bias.

3.7.2 Validity, generalizability, reliability

Qualitative research conducted within a flexible strategy is particularly vulnerable to threats to the validity of the research, where the quality of the researcher directly determines the quality of the research undertaken (Robson, 2002). In addition, Creswell and Plano Clark (2009) recognises trustworthiness, authenticity and credibility as attributes which should be true of the researcher and therefore enhance the validity of the research. Furthermore, Stake (1995) recognised that researchers need to be both accurate in measuring ‘things’, alongside being logical in the interpretations made. The techniques used to address the validity, generalizability and reliability of the study are presented in Table 3.10 and discussed in the following paragraphs.

Table 3.10: Overview of techniques used to address validity, generalizability and reliability within the study based on assessment criteria advocated by Yin (2003).

Assessment criteria for quality of research design	**Techniques used**	**Phase of research**
Construct Validity Establishing correct operational measures for concepts being studied.	Collection of multiple sources of evidence	Data collection (Section 3.6.1)
	Maintenance of a chain of evidence.	Data collection (Section 3.6.1)
	Review of the research outputs by participants within the study.	Composition of research findings (on-going throughout research through reference group meetings, focus groups)
Generalizability (External Validity) Establishing the domain to which the study’s findings can be generalised.	Analytic generalisation based on theory within the single case study.	Research design (Section 3.3)
Reliability Demonstration that the operations of a study can be repeated (e.g. data collection)	Development of a case study database	Data collection (Section 3.6.1)

Construct validity

Through the triangulation of evidence from multiple data sources (e.g. internal company documents, industry documents, observations, European Legislation, academic literature, interview transcripts), increased validity in the research is achieved. Throughout the data collection phase, the relationship between the data, analytical activity and the research questions were identified and noted within the Microsoft Excel® case study database. Each source of evidence was categorised against the research questions which were initiated at the commencement of the study. Through this process, a chain of evidence was established between the data collected and the research questions posed for the research. During the conduct of the research, as findings were being developed from the evidence, these were fed back to the reference group for discussion and comment. Therefore experts within the field were able to contribute to, verify and dis-regard any of the findings made by the researcher.

Generalizability (External generalisation)

The research has focused on one case study organisation, which can be perceived to be an inadequate basis for external generalisation (Yin, 2003). Within case study research the focus is on analytical generalisations, and therefore the purpose is to generalise the specific findings to a broader theory. The generalizability of the findings from the study are related back to the theoretical body of literature which supported the development of the study, therefore attaining analytic generalisation of the study to the broader theory and applied context. This was conducted for the development of the Hybrid-DSP in relation to the theoretical principles of decision support development and application. Furthermore the development of the Hybrid-DSP itself is founded in the principles of the theories of decision making, along with the observations made within the organisation. Therefore the Hybrid-DSP itself has application across a wider field of organisational contexts where uncertainty and complexity in decision making is apparent.

Reliability

To increase the reliability of the research, a database of all data and sources of evidence collected and used within the case study was developed during the research. Two forms of the database were developed, an indexing system database to allow selection of significant sources of data, to be used within a qualitative data analysis software programme (QSR NVivo 9, see section 3.6.2). The databases served two functions. Firstly they improved the ability of the researcher to manage and interact with the sources of evidence and allow for the final case study report and discussion to be presented within the thesis. Secondly they provided for external audit of the evidence used to form the arguments and findings presented within the thesis. Furthermore, the research database provides reference back to the research questions for each of the sources of evidence collected. Therefore a chain of evidence which reinforces the validity of the research is achieved through the use of the case study database.

3.7.3 Ethical considerations

Within qualitative case study research, the context of the research is explicitly incorporated within the research, through the participants involved in the study and the documents and data from the organisation within which it is conducted (Robson, 2002). Throughout the research details related to individuals within the organisation, and organisational documents and data have been used, based on an agreement to maintain the confidentiality of the data. The agreed terms and conditions for the study between the organisational sponsor and the university facilitated the use of specific details regarding data used in the research and in the final production of the thesis.

Throughout the conduct of the research the student was known to the staff within the organisation as a researcher exploring the implications of the WFD on the management of potable water supply through the development of a decision support system. During all meetings, informant discussions and interviews, the researcher was introduced as "a researcher" and information generated during these occasions was understood to be for the purposes of the research. Where specific details were to be regarded as confidential, these were highlighted and acknowledged by the researcher. The case study organisation has provided express permission for data to be used openly within the thesis, although within the thesis ID references for informants have been used, whilst the full details of the informants are provided within Appendix C.

3.8 Case study organisation and context

Anglian Water Services (AWS) (referred to interchangeably in the thesis as the "water company" or the "organisation") is geographically positioned on the eastern side of the United Kingdom, and provides water and wastewater services to 18% of the land area of England and Wales, which is approximately 27,000km^2. AWS operates within the lowest lying area in England and Wales which is on average only 69 meters above sea level. Potable water sources are abstracted from rivers (5%), groundwater (50%) and reservoirs (45%) and distributed within 36,800km of water main networks to 4.2 million people. Of these customers 42% live in rural areas, and 62% are in unmetered households (AWS, 2007a). Figure 3.8 illustrates the main population centres served together with the location and types of water sources used across the Anglian Water region.

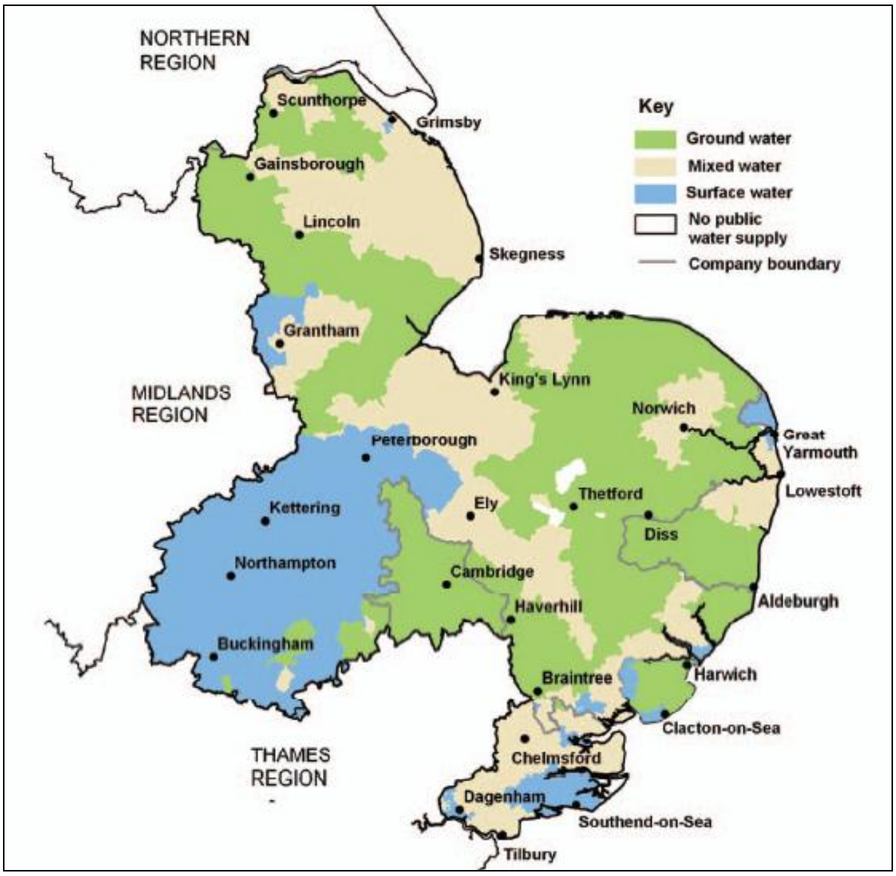


Figure 3.8: Potable water sources in eastern England (DWI, 2007)

Increasing pressure on the management of water resources is a continual problem exacerbated by increasing population growth and the impact of a changing climate (AWS, 2007a). The region also has more EU designated water-dependent conservation sites than any other water company, which presents an additional constraint for the management of water resources (AWS, 2010). Flexibility in the use and availability of water resources allows sources to be mixed and adapt to changes in localised environmental factors affecting potable sources. This enables water demand to be met in different geographic areas as well as allowing potable water quality standards to be achieved. Treatment challenges for groundwater and surface water are different. Groundwater sources are treated with simpler processes (e.g. blending, ion exchange) followed by disinfection of the potable water on entering the distribution network.

Surface water from rivers and reservoirs requires more complex treatment which can involve six stages; ozonation, coagulation, sedimentation, filtration, adsorption and chlorination (AWS, 2006a; Baruth, 2005). The quality of the water source used, also determines the treatment stages required, thus any short-term or long-term changes in water quality have a direct impact on the treatment process employed.

In more recent unpredictable weather conditions with extreme events occurring, combined with changes in the legislative management of pollutants entering water bodies, the risks facing the treatment process are both varied and complex. Thus flexibility in the management and treatment of water in response to the environmental and legislative uncertainties is of interest to deliver long-term service to customers. The long-term management of potable water resources are documented in reports produced for the regulators. These reports include; the Water Resources Plan, the Drought Plan, and the Water Efficiency Plan (AWS, 2007a) and more recently the Water Resources Management Plan (AWS, 2010). The decision support systems used within the organisation for the management of water resources include CRAGS, SWRA, Risk and Value, Asset Plus+, FORWARD, and DWSP. Details regarding these systems are discussed in Chapter 4.

In 2007, the production of the first 'Anglian Water Strategic Direction Statement' (SDS) identified the strategic priorities for AWS with the goal being *`to deliver a reliable supply of clean, safe drinking water and effective wastewater services at an affordable price'* (AWS, 2007a). To achieve this seven central strategic priorities for the next 25 years have been identified. These are; increase the resilience and reliability of our water and wastewater services; secure and conserve water resources; anticipate and invest for growth in our region; improve the environment in our region; mitigate and adapt to climate change impacts; improve our efficiency and flexibility; and to keep bills at current affordability (AWS, 2007a).

The Water Framework Directive (2000/60/EC) came into force on the 23rd October 2000. The purpose of the Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater.

Implementation of the WFD involves six year cycles of River Basin Management Plan (RBMP) development which is a challenge for synchronisation with the five year development cycle of Asset Management Plans (AMPs) (Appendix B). The implications of the Directive on the management of wastewater across the water industry have been and are continuing to be studied although the impact of the Directive on the treatment of potable water resources is still unknown. Anglian Water have identified this as a potential threat to the business if it is not managed, and thus research is required to understand and manage these uncertainties. Therefore, through the case study organisation of AWS, a Hybrid-DSP is developed to assess the impacts of the WFD on the management of potable water resources, whilst also gauging organisational responses to the use of the Hybrid-DSP.

3.8.1 Hybrid-DSP development

The Hybrid-DSP was developed to explore and understand the implications of the WFD on the management of potable water, incorporating both general implications from the WFD combined with a site specific case study which was selected in conjunction with the research participants (IM 6, IM 10) and through reference group meetings (RG1,2 and 3). The site selected was chosen to explore the impact of the WFD on the management of nitrate in groundwater, and the implications for the management of potable water resources and treatment at Barrow WTW in North Lincolnshire. The location of Barrow WTW and the surrounding catchment, which includes the local groundwater ‘source protection zones’ (SPZs) is illustrated in Figure 3.9. The geology around the Barrow WTW is principally chalk, and the water source is located within a confined aquifer. Three other sites (Barton, Goxhill and Thornton) also supply groundwater to the Barrow WTW. The groundwater catchment is approximately 91.6 km^2, and is predominately arable agricultural land, with some livestock kept within fields close to the borehole site at Barrow. The treatment process at Barrow consists of ion exchange, chemical dosing (chlorine, sulphur dioxide, fluoride, orthophosphoric acid), and blending. The details from the general and site-specific assessment of the implications of the WFD for potable water management are detailed in Chapters 4 and 5.

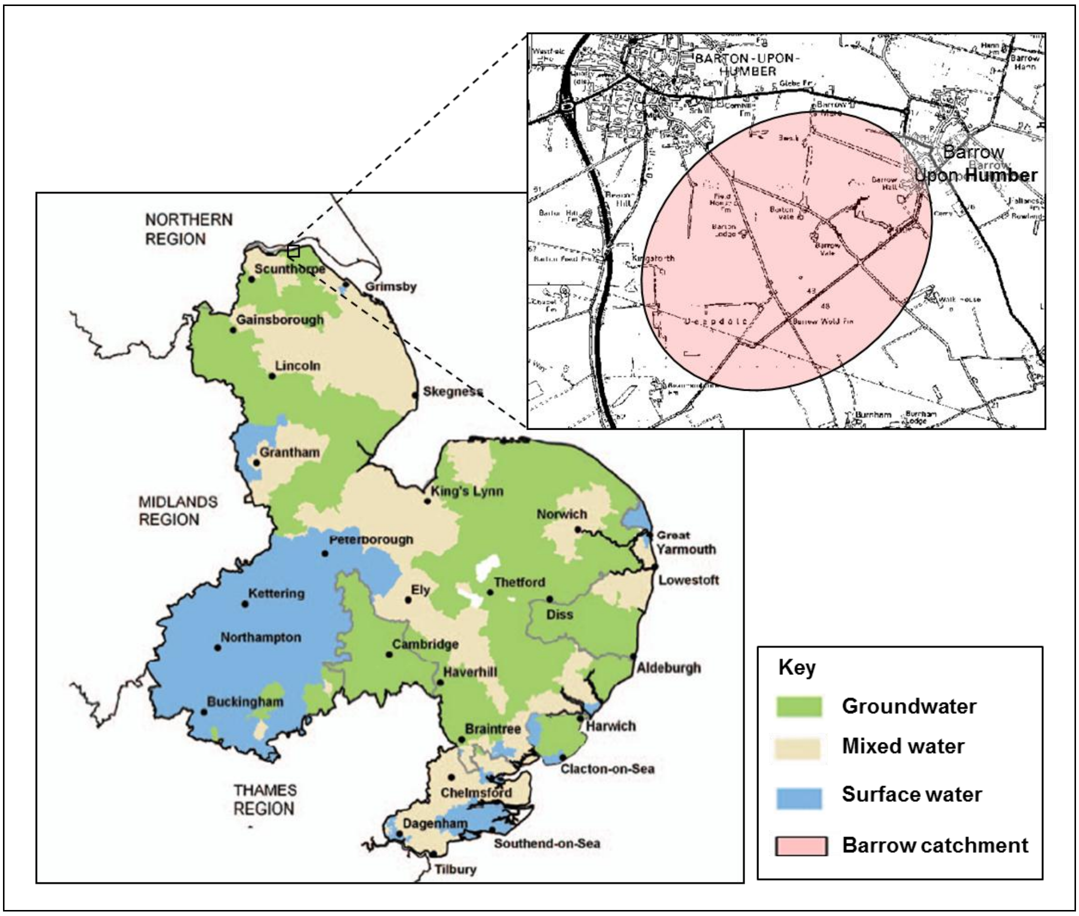


Figure 3.9: Location of Barrow and surrounding catchment (adapted from DWI, 2007 and AWS, 2007b:5)

3.9 Reflections on the research process

During the research, as commonly expected in applied research, the researcher was exposed to many real-time events which provided specific knowledge on the operation of the organisation, but also presented many challenges in conducting research. Availability of participants in the research, and the timing of business activities (e.g. the preparation of the business plan, and the responses of the organisation to the EA requirements for data and information during the development of the PoMs and RBMPs) presented difficulties in planning meetings and proposed workshops, when all participants would be available. The dynamic nature of the implementation of the WFD, with multiple documents and guidance being released as well as new daughter Directives from the WFD, resulted in the researcher having to process and interpret many new documents which informed the design and provided data for the application of the Hybrid-DSP. Although this provided real-time and current information, maintaining a current knowledge of the operating and the developing legislative environment, whilst also designing and applying the Hybrid-DSP using BN software was a challenge. The interviews conducted were a useful method to obtain detailed information, although the failure of the recording equipment meant that specific detailed perspectives were not able to be captured as accurately. During the conduct of the RG and FG meetings interesting data and evidence was obtained regarding specific case study details from multiple perspectives. The format of these meetings promoted and encouraged an active and overall enjoyable learning environment, which also allowed for additional participants to be involved within specific meetings. However through the research, the generation of a large database of qualitative information provided specific challenges for the analysis. The extensive number of documents, transcripts, field notes and observations, which although providing both data and methodological triangulation, also presented a challenge in conducting data analysis with regard to the time required and managing the large data set. Using the NVivo software within this context, therefore presented an opportunity for the researcher to engage with and draw conclusions from the data set more easily.

Conducting action research therefore requires extensive investment in time in getting to know the operational environment, identifying contacts and building relationships with participants, identifying data sources, as well as keeping the focus and momentum with those participating in the research. All these features offer an exciting setting for conducting research, although as the researcher found, it is also highly demanding to manage.

3.10 Summary

Chapter 3 has presented the basis on which the research has been conducted, including discussions regarding the research strategy adopted, the research methods implemented, and the analysis process conducted. The results of this research are subsequently presented in Chapter 4 and 5.

4 Development of the Hybrid-DSP

4.1 Overview

This chapter aims to address RQ 2.1 to RQ 4.1 through the design of a BN based Hybrid-DSP. A review of the case study organisations' decision processes for investment in potable water management is conducted (RQ 2.1-2.2) which contributed to the establishment of criteria for the design of a Hybrid-DSP (RQ 3.1). Methods and techniques are selected and their application discussed (RQ 3.2, RQ 3.3, RQ 3.4), whilst also revealing organisational perspectives of, and responses to the techniques used within the Hybrid-DSP (RQ 4.1). These activities, engendered an understanding of the problem domain by both the participants and the researcher, whilst also informing decisions regarding potable water management within the organisation in response to the WFD.

4.2 Introduction

The research approach to the development of the Hybrid-DSP has previously been presented within Section 3.4.3, and summarised in Figure 3.4. Data sources used and the analysis conducted are identified in Section 3.6 (and summarised in Figure 3.5). This chapter presents each of the seven stages of the Hybrid-DSP development, within Sections 4.3 to 4.8, although Stage 6 is presented in more detail within Chapter 5. Throughout this current chapter reference is made to the sources of information and data used, which are referred to directly or through the use of the following acronyms: reference group meetings (RG), focus group meetings (FG), informant meetings/ discussions (IM) along with the identity number (ID) of informants.

4.3 The problem domain

Stage 1 of the Hybrid-DSP development involves the determination of the problem, which is informed from general case study contextual data and by answering RQ 2.1 and RQ 2.2. The problem context as previously introduced in Section 1.2, Section 2.8 and Section 3.8 embraces the changes in the strategic environment of the water company, in relation to the implications arising from the implementation of the WFD. Of interest is the specific impact these implications have on the management of potable water by a water company. Uncertainty and complexity are dominant features within this problem domain, resulting from changes in events external to the water company (e.g. WFD implementation), and internal changes related to the development of Asset Management Plans (AMPs) and a new drinking water safety planning (DWSP) risk assessment process. The timeframe over which these significant events occurred within the problem domain has been previously presented in Table 3.3 (see Section 3.4.3). In response to these challenging conditions, the development of a decision support process would offer a more formal process to analyse the impacts of the WFD on organisational decisions related to potable water management.

Within the frame of the broader problem domain, the selection of a specific case study for the development of the Hybrid-DSP was determined in liaison with representatives from the water company. This was established during the initial reference group meetings (RG 1,2,3) as described in Section 3.6.1. A site specific case allowed for an assessment of the WFD impacts at a specific location although the impacts identified were also recognised at a general level for water management. The case study selected involved a groundwater source abstracted from a limestone aquifer in North Lincolnshire (Barrow WTW) (see Section 3.8.1), with a focus on nitrate concentrations in abstracted water and the subsequent management options available. Nitrate contamination is a known problem at this site, which presented an opportunity to explore how nitrate management at the surface may change in response to the implementation of the WFD and consequently how these changes may affect the currently rising nitrate concentration (AWS, 2009b). This case is representative of the threat nitrate contamination poses to potable water supply across the Anglian region, and as such is an issue of high priority for the water company. Agricultural sources of nitrate contamination in groundwater are recognised as an on-going environmental concern, especially across the mostly arable landscape of the Anglian region in the UK (EA, 2009a). The presence of high nitrate in water sources has both human health and environmental eutrophication implications and therefore requires tight regulatory control. A limit of 50 mg/l for potable water has been set by the Drinking Water

Directive (98/83/EC), however a limit of 45 mg/l is used for operational control within the case study water company for potable supplies, to ensure compliance. The farming systems used have a direct influence on the amount of nitrate released into the water environment (e.g. nitrate application as a fertiliser, ploughing up of grassland resulting in nitrate mineralisation of the soil). However, through the WFD implementation the way in which direct and point sources of pollution are being managed in locations where water is used for potable supply is changing, with the introduction of a range of legislative measures (e.g. safeguard zones, water protection zones). These measures would have a direct impact on the farming practices used. When, where and how these measures will be implemented has been a source of uncertainty during the research, and continues to be as the effects of these measures are still unknown.

> "*there still seems to be a little bit of uncertainty around the WFD with certain things like, the whole idea of source protection zones, and the status of safeguard zones, generally in protected areas, water protection zones, and how they are going to be interpreted, it's still on-going work*" (INT 5[ID73] 09/09/2009).

Mitigation of the risks within the wider catchment have not always been taken into account in the development of strategic investment plans by water companies within the UK due to the economic regulation of the water industry. Investment has traditionally been driven by service standards to customers, environmental standards and drinking water health standards, resulting in a focus on technological solutions to address potential asset performance. In cases where the water industry does not own or is not in control of the management of assets or interventions, investment has not historically been encouraged by the economic regulator (Ofwat). Throughout the research period (especially during AMP development), the position taken by the regulators regarding potential alternative investment options (e.g. catchment management, the success of which is jointly dependent on factors outside of the control of the water companies), was a significant source of uncertainty.

> "*Ofwat could very likely say well we're not going to agree this funding because what's the point of us agreeing that customers should be spending thousands of pounds, for a very small benefit*" (INT4 [ID 31] 04/09/2008)

During the last PR09 period, a ground-breaking position taken by Ofwat allowed investment into catchment investigations for the first time. This change reflected a major emphasis on integrated decision making with regard to water resources as set out in the WFD, which now promotes a wider range of investment options to manage potable water resources.

> "*At the 2009 price review, we supported the companies' proposals to spend £60 million on more than 100 catchment management schemes and investigations*" (Ofwat, 2010a).

The components of this complex and uncertain problem domain are illustrated in conceptual models (Figure 4.1 and Figure 4.2) which were identified during RG1, 2 and 3. These bring sharply into focus the relationships between the human (stakeholders and organisations governing potable water management) and the physical environment. The implications of the WFD across the water supply chain are also overviewed in Figure 4.3 highlighting the extensive implications at the catchment level as opposed to the treatment level of potable water.

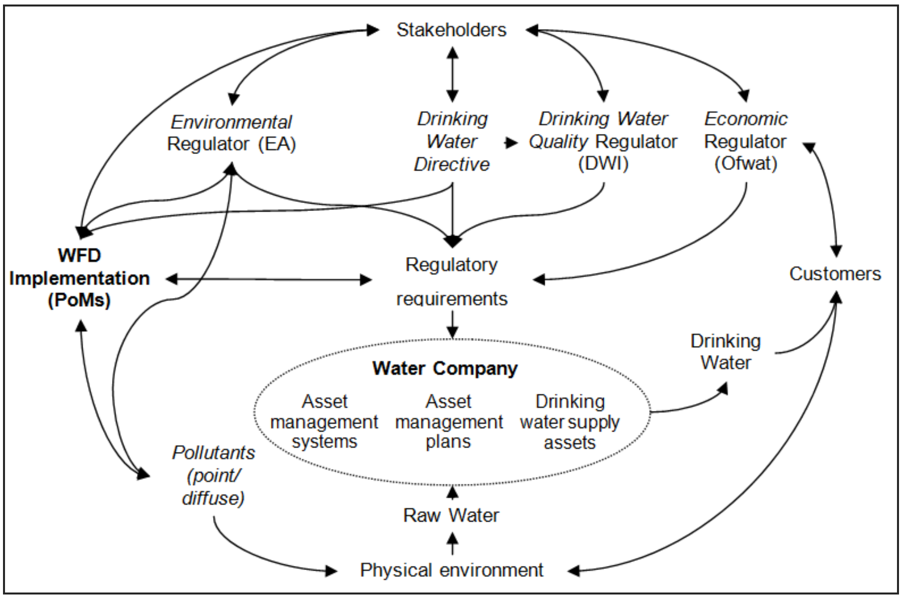


Figure 4.1: Conceptual model of the associations between main stakeholders and other elements of the problem domain.

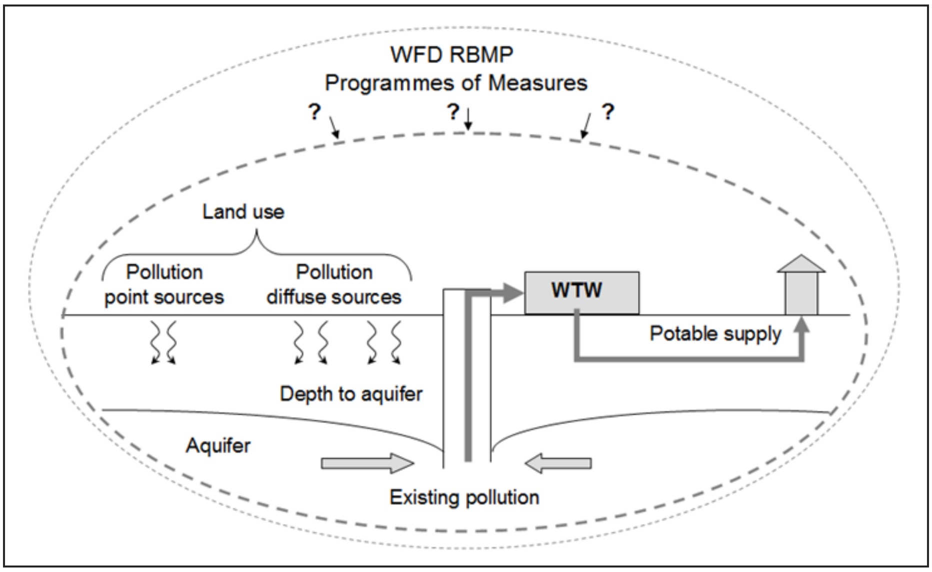


Figure 4.2: Conceptual model of the physical environment within the problem domain linking the catchment level, groundwater abstraction, water treatment and water supply.

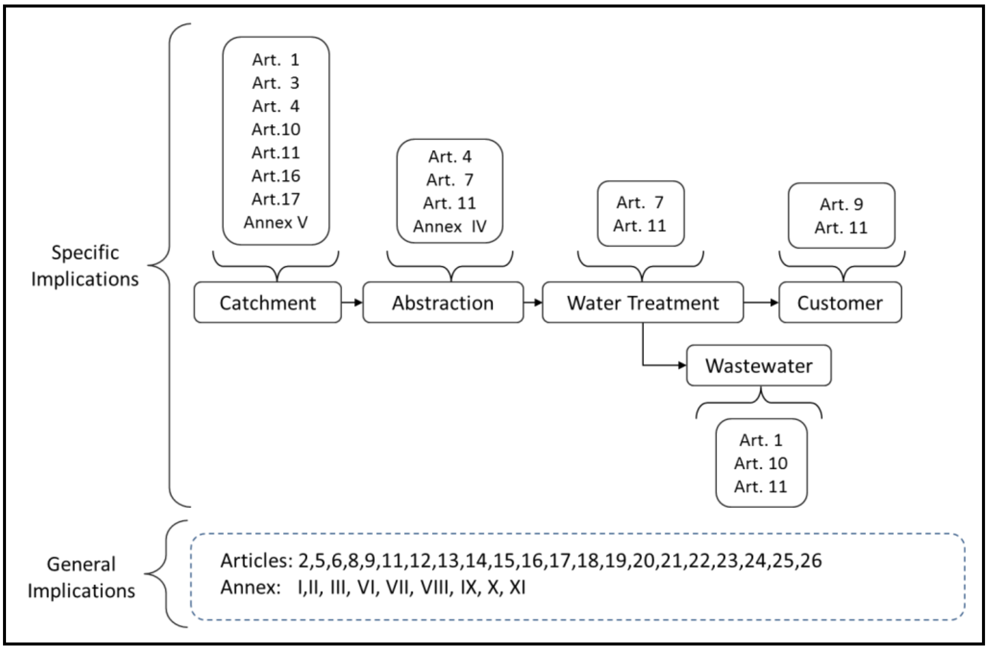


Figure 4.3: System view of the relationship of the WFD articles to the potable water supply chain.

4.4 Purpose and requirements of the Hybrid-DSP

The purpose and requirements of the Hybrid-DSP are presented in this section to achieve Stage 2 and 3 of the Hybrid-DSP development and address RQs 2.1, 2.2 and 3.1. To identify the purpose and requirements a review of the existing water company systems and processes for handling the uncertainties related to environmental legislation (e.g. WFD) implementation (as detailed in Section 4.3) was undertaken. In addition, the perspectives of reference group members were sought regarding the criteria for a Hybrid-DSP, which were also followed up through semi-structured interviews. Therefore, the development of the Hybrid-DSP was guided from the deficiencies in the current organisational decision making systems, the overarching decision making approach being promoted by the WFD, as well as the features of decision support development (see Chapter 2).

4.4.1 Organisational decision making processes for WRM

Through an on-going review of current decision support systems and processes within the case study organisation (hence addressing RQ 2.1), an assessment of the available capabilities to incorporate the impacts of environmental legislation (e.g. the WFD) on potable water management was conducted. The decision support processes and systems identified within the organisation for the management of water resources included CRAGS, SWRA, ‘Risk and Value’, Asset Plus+, FORWARD, and DWSP, which have been summarised in (Table 4.1).

Table 4.1: Overview of the decision support systems and processes within the case study water company for the management of water resources

Name of process/ system	Purpose	Operational time period	Reference
Asset Plus+	Asset Investment Management System, utilising specific software. Asset Plus+ provided a basis for the management of risk for asset lifecycles along with performance and cost trade-offs..	2009 onwards	AWS (2009a).
CRAGS (Contamination Risk Assessment for Groundwater sources)	Risk assessment process to identify existing and potential risks to groundwater potable sources.	2003 onwards	AWS (2003)
Drinking Water Safety Plan (DWSP) and Hazard and Control Templates	Risk assessment process to identify hazards to potable sources and control measures.	2008 onwards	Staunton and Holtby (2008)
FORWARD (FORecasting of WAter Resources and Demand)	Forecasting supply and demand for potable water, using computer based modelling.	2004 onwards	AWS (2008a), AWS (2010)
Risk and Value intervention process	Manual risk assessment process of operations and potential service failure, therefore a need for investment is identified, and developed into a required investment programme.	2005 onwards	James (2005), James (2008), AWS (2009b)
SWRA (Surface Water Risk Assessment)	Risk assessment process to identify potential risks to potable surface water sources	2006 onwards	AWS (2006c)

Developments in organisational processes and systems during the research period included the design and implementation of a new Asset Plus+ software system, (building upon the ‘Risk and Value’ process used previously in AMP4 [INT 4]), to centrally manage investment schemes to be put forward into the business plan. In addition a new drinking water safety planning (DWSP) approach was being developed to understand existing risks to the potable water supply chain for surface and ground water sources. During these uncertain and complex changes, the researcher had to iteratively design criteria and identify integration opportunities for a new Hybrid-DSP within the organisation. The assessment of the water company systems and processes was conducted through liaison with informants within the water company, semi-structured interviews, researcher observations and water company documents. The sources of evidence used in the assessment of the systems are summarised in Table 4.2.

Table 4.2: Sources of evidence to support the assessment of existing systems used by AWS for decision making for water resources management

Decision support process	Semi-structured Interviews	Documentation	RG /FG meetings	Observation	Informal discussion
Asset Plus+	INT8 [ID34] (23/09/2009)	Water company AMP Section B3 (AWS, 2009b)	RG 5 – open discussion on how DWSP and Asset Plus were used. FG 3 – discussed Asset Plus performance with Asset Management consultants who designed Asset Plus.	ID19 demonstrated Asset Plus during a discussion with the researcher (28/04/2009)	Discussions regarding the use of Asset Plus and incorporation of environmental legislation implications (e.g. WFD) with the following informants (IM10 [ID34] 07/02/2008); (IM37 [ID34] 26/11/2008); (IM47 [ID19] 28/04/2009) ; (IM49 [ID67] 13/05/2009) (IM61 [ID67] 22/12/2009)
CRAGS	N/A	Water company CRAGS process (AWS, 2003)	N/A	DWSP workshop (29/04/2008) (presentation of its use)	(IM6 [ID73] 08/11/2007)
DWSP	INT5 [ID70,ID73] (09/09/2009))	Water company internal guidance on DWSP (Staunton and Holtby , 2008)	RG 5 – discussed its use.	Researcher observations made at a DWSP workshop in North Lincolnshire (29/04/2008)	(IM47 [ID19] 28/04/2009) (IM20 [ID70] 09/05/2008)
FORWARD	N/A	Water resources management plan – details of the process. (AWS, 2008a; AWS, 2010)	FG1 – discussed with ID34 the historical data used.	N/A	Discussion with ID77 (on 01/05/2008) regarding its use and performance.
Risk and Value	INT8 [ID34] (23/09/2009)	Water company manual for Risk and Value (James, 2005; James, 2008).	RG 5 – open discussion on how Risk and Value (R&V) related to Asset Plus	N/A	(IM45 [ID59] 14/03/2009); (IM10 [ID34] 07/02/2008); (IM37 [ID34] 26/11/2008);
SWRA	N/A	Water company SWRA process (AWS, 2006b)	N/A	DWSP workshop (29/04/2008)	(IM27 [ID30] 10/06/2008)

A SWOT analysis was conducted using the various sources of evidence identified in Table 4.2 with a summary of the main issues highlighted in Table 4.3. This analysis provided guidance and criteria for the design of the Hybrid-DSP which are detailed in Section 4.4.3.

Table 4.3: Summary of the strengths and weakness of current decision support systems within the case study organisation

Strengths	Weaknesses
• Historical data available to inform processes (incidents/events/risks) [CRAGS, SWRA, FORWARD, DWSP, Risk and Value, Asset Plus+] • Catchment level data incorporated [CRAGS, SWRA, DWSP] • Data held in multiple sources. • Multiple formats of data suitable for internal use and reporting to regulators (e.g. CRAGS = word document reports, DWSP = spreadsheet based, Asset Plus+ = software based.) • Projections for investment decisions for WTWs are made on historical trend analysis. [CRAGS, FORWARD, Asset Plus+] • Risk scores for assets are identified to inform investment requirements [DWSP, Risk and Value, Asset Plus+] • Integration of data from other systems [e.g. DWSP, uses data from CRAGS, SWRA, Crystal QD Warehouse]. • Incorporates multiple factors [e.g. social, environmental and economic in Asset Plus+] • Promotion of organisational understanding of the risks affecting the potable water supply chain [DWSP] • Participation and organisational learning promoted through interactive workshops [DWSP, Rick and Value]. • Performance of assets are measured using a risk profile over time to identify potential impacts on services measures and hence trigger investments [Asset Plus+].	• Multiple sources of data used for different systems, not centrally stored (e.g. on separate spread sheets within separate departments). • Data stored in different formats not easily accessible for analysis[e.g. Microsoft Word ® documents or spreadsheets in Microsoft Excel®] • No inclusion of data from future scenarios, regarding water quality trends [CRAGS, SWRA, Risk and Value, Asset Plus+]. • No inclusion of the effects of environmental legislation (WFD) on future raw water quality [all systems]. • Limited incorporation of future changes in events and scenarios on the management of assets. • Limited incorporation of multiple factors (e.g. legal compliance issues, technological issues, social issues, and environmental issues) within one system or process. • Output identifies a 'static' risk score attributed to an event, which does not represent a distribution over a range of states for a given parameter. [e.g. CRAGS, SWRA] • No inclusion of future control or intervention measures at the catchment scale [all systems]. • Limited consideration of the 'need' for an asset, only to maintain existing assets and further development of assets. [Risk and Value] • No incorporation of potential reduced risk to assets due to improved raw water quality resulting from the WFD [Risk and Value, Asset Plus+]
Note: systems in [ ] are specifically related to the point identified.	

The DWSP offered an assessment of risks to potable water sources through the use of the ‘hazard and control templates’, although these only “*look[ed] at the risk today, they have no forward looking element, they only have backward looking*” (FG1 [ID34], 03/11/2009). Therefore when discussing the performance of the DWSP, related to forward looking investment, ID34 highlighted they “*don`t feed in particularly that way*” (FG1 [ID34], 03/11/2009). The use of ‘Risk and Value’ also had an emphasis on operating and maintaining existing assets, as opposed to questioning if the assets would be required under future operating conditions. Hence these processes had an emphasis on the management of the existing assets based on existing and historical information, rather than considering the implications of future environmental, economic or legislative changes.

During AMP4 the ‘Risk and Value’ process informed the development of proposed investment plans, focusing on the cost of alternative options. The process recently adopted towards the end of AMP 4 going forward into AMP5 (Asset Plus+) now includes a wider range of factors when determining investment options. “*‘Risk and Value’ is about investment decision making only, Asset Plus+ has a lot more problem identification in it. The main difference in the process side of things is the inclusion of social and private costs in the valuation ~~of~~ [within] Asset Plus+, Risk and Value only uses private costs”* (INT8 [ID34] 23/11/2009). Although Asset Plus+ is incorporating additional social and private factors in the decision process these are not specifically related to the effects of the WFD implementation. The other systems and processes (CRAGS, SWRA, DWSP and FORWARD), are also restricted to physical factors related to the risks to the management of potable water (e.g. environmental factors included in CRAGS, SWRA, DWSP; as well as the inclusion of population size in DWSP and FORWARD). Explicit incorporation of WFD specific factors related to changes in the wider catchment affecting the management of potable water resources was limited, with only initial proposed schemes incorporated within the National Environment Programme (NEP) (see Section 4.4.2).

During discussions with ID34, ID39, and ID45 within FG 2, the performance of Asset Plus with respect to managing WFD implications was discussed. Although routine investments are managed within Asset Plus+ through the 'Investment Manager' component, 'one off' investments, as identified by ID39 and ID45, were not able to be incorporated. Therefore specific investment options such as "catchment management" would not necessarily be able to be calculated within Asset Plus+. In addition, if investments were targeted at a regional scale (as opposed to specific water treatment works), implications for the management of investment options within Asset Plus+ were also highlighted to be a difficulty.

Prior to the WFD, investment decisions for potable water abstraction were based on plotting historical trends of contaminants (e.g. nitrate), and identifying when they would exceed DWD limits (e.g. 50 mg/l). Where expected exceedances were predicted, investment in nitrate removal technology was instigated, as expressed during an interview with ID 70 on 09/09/2009 who commented that the typical response of a water company was to just "*bolt on another treatment process*". The possibility of getting involved in catchment management had not been seriously considered previously. The attitude being to "*let the Environmental Agency worry about the catchment that's their job*" (ID73, [09/09/2009]).

Interviews conducted with the reference group members highlighted their perspectives of the current investment decision making process. Members identified that their current systems do not consider the WFD as a main driver to inform investment decision making, which may explain the limited consideration in the existing processes and systems. Perspectives of the process are presented below, although it should be noted these were provided during an uncertain period in the regulatory period affecting investment planning. .

> "*Our formal investment process is more to do with drinking water compliance, not the Water Framework Directive*" (ID73, 09/09/09)
>
> "*Our investment decision making process is based on our data, our monitoring data, our nitrate trending analysis, that's the hub of it, and then we've identified the rising ones which are going to fail the drinking water directive, in AMP 5*

> *then we've projected and said well these ones are going to fail in AMP6 or AMP7.*" (ID70, 09/09/09)

The reference group members however, did recognise that they [AWS] need to understand in more detail what the WFD implications are going to be and hence identify appropriate investments.

> "*if the WFD PoMs are nitrate vulnerable zones, and catchment sensitive farming then, we`ve got to work out how effective they are going to be, and get involved in the process, so we can make the right planning decisions for the future*" (ID73 09/09/09)

During the dynamic period between 2007 and 2010 significant changes in the role of water companies in relation to the management of the catchment were taking place. To adjust to these changes the water company had to review and identify existing and alternative investment responses.

> "*it has changed dramatically in the last couple of years, as to what we are expecting to do, to take on this role and get a greater understanding of the catchment, and what's going on and what the likely risks are*" (ID73, 09/09/2009)

These perspectives highlight the change in stance for decision making by the water company in the management of risks; from failure of meeting the DWD (addressed through investing in treatment), to reducing the risks affecting the potential failure of potable water standards (through catchment interventions). These changes are a result of both the development of DWSP to address risks to the potable water supply system, as well as the WFD requirements for sustainable management of water resources and hence preventative management of water pollution.

Therefore from the review of the existing systems, criteria to be included in the design of the Hybrid-DSP include: i) incorporation of a forward looking assessment of the impacts of the WFD, ii) incorporation of multiple criteria for investment decision making, iii) incorporation of WFD specific features and measures to management water sources.

4.4.2 WFD implementation and organisational decision making

In this section how the implications of the WFD were incorporated into organisational decision making and hence investment planning is further discussed, to address RQ2.2. The organisational systems and processes reviewed in Section 4.4.1 identify that, the WFD was not explicitly included in any organisational process or system. However, implications from the WFD were incorporated into the investment plan through the National Environment Programme (NEP) during the preparation of the business plan (INT7 [ID31] 22/09/2009). Decision making regarding identification of investment implications for the water company in response to the WFD were progressive through the iterative release of information from the EA during the draft and final RBMPs (EA, 2009a). The formation of an internal WFD Working Group (WFD WG), as well as individuals working with the Environment Agency (EA) identifying specific requirements e.g. through the Working Together initiative (WTi) (INT7 [ID31] 09/09/2009), provided a consultative base to understand the WFD requirements, and hence identify organisational decisions.

The WFD WG was set up to address and communicate the development of the WFD and identify the implications for the water company. In April 2005 the terms of reference which stated the purpose and responsibilities of the group were established. These included the purpose of "*ensuring effective and appropriate communication of WFD issues or requirements"* and the responsibilities of *"developing [the water company] strategy and approach to the Water Framework Directive", "to secure fair and equitable funding for such programmes of measures which regulators deem appropriate"* and to *"ensure an appropriate and timely response to formal consultations relating to the WFD"* (Harward, 2005). The WFD WG had therefore taken on the ethos of the WFD through prompting participation and engagement across the business to identify the WFD implications and contribute towards the on-going WFD implementation process at the regional and national level.

Although the terms and conditions set out the ambitions of the group, observations made by the researcher through attendance at the WFD WG meetings (WFD 1,2,3 and 4) highlighted that no clear or structured process for understanding the implications of the WFD was in place. Instead incremental WFD developments were identified and communicated to the wide range of business unit representatives at the WFD WG meetings for discussion. Consequently, the information was disseminated within the water company, whilst also seeking consultation within the organisation on specific developments (e.g. the implications of the PoMs to be included within the RBMP). The implications of the WFD for the development of the strategic business plan and the priorities for investment were also discussed, specifically where draft Programmes of Measures (PoM) were identified. Most of the issues were focused on the wastewater aspects of the business where improvements in discharges to water bodies were required. The specific improvements for wastewater discharges became part of the investment projects within the AMP through the NEP (INT 4 [ID31]).

Where the impact of the WFD concerned management actions across the wider catchment, a mechanism to understand and identify the implications for the provision of water for potable supply and impact on treatment had not been identified (INT 6 [ID09], INT 4 [ID31], INT 5 [ID70,73]). Instead the newly formed NEP driver for investment "WFD 5" was used to propose investigational work to look into the catchment activities affecting sources of water used for abstraction. The justification of a catchment management approach was twofold through the drinking water safety planning (DWSP) process, which highlighted sites which were at risk of failing DWD standards, as well as supporting the management activities through the PoMs proposed within the draft RBMP. However, specific reference to catchment management had not been made in the draft RBMPs, and hence organisational commitment to catchment management was still uncertain (ID31 discussion in RG 5).

Observations made by the researcher during the RG meetings, WFD WG meetings and informal discussions with water managers, highlighted that an understanding of the WFD across the representatives at the WFD WG meetings was limited resulting in limited engagement or active debate and discussion around the issues presented for discussion. For example, when seeking engagement with the WFD WG on their comments on the draft PoMs, the group was limited in their response both within the meeting, and when asked for further comments after the meeting (WG 2 and 3; INT 4

[ID31]). The members of the WFD WG who had more direct involvement in the WFD and its implementation did however engage in more detailed discussions (e.g. ID64, ID70, ID73, ID33, ID31). This was also evident during earlier reference group meetings (RG 1, 2, 3, 4), although further understanding and awareness was also developing during this time through representation of reference group members involved in additional 'Article 7 sub-groups' (ID73), and EA 'Joint Business Teams' (ID31, ID 70) linked to WFD implementation.

In addition ID73 highlighted their concerns over the exact role of a water company in the implementation of the WFD, which further emphasizes limited understanding of the position and responsibilities of the water company in response to the WFD.

> "*I mean the WFD from my angle is just so .. not ill defined,.. but a bit ambiguous as to what the water companies are supposed to be doing, we have our agenda which is water quality, and water quantity, and a lot of the legislation covering that has been in place before, whether the impact of the WFD is that it gives an onus on the competent authorities to start reducing trends, which is in our interest, so what's the point of that*" (INT 5, [ID73] 09/09/2009).

The research period highlights the high level of uncertainty around the implications of the WFD and the uncertainty as to the roles and responsibilities of the water companies. This presents a further level of complexity for the management of both the WFD, the identification of the organisational investment options, and hence the design criteria of management options to be included in the Hybrid-DSP.

Therefore, during the observations made by the researcher and supporting evidence from interviews of the organisational process for decision making within the water company in relation to the WFD implementation, three main criteria to be incorporated into the design of the Hybrid-DSP were identified. These being: (i) a structured process to understand the impacts of the WFD, (ii) an educational and interactive method to engage the organisation and support inter-departmental learning related to the impacts of the WFD, (iii) a process to systematically identify potential organisational response to the WFD, rather than ad hoc responses to specific details of the WFD.

4.4.3 Decision support criteria

As indicated in Section 3.6, the decision support criteria were iteratively identified through a review of the WFD, discussions with the case study organisation and informed from the decision support literature. The main themes, and hence development criteria for the Hybrid-DSP are reported in Table 4.4. These criteria form the basis for the development of the Hybrid-DSP, whilst also providing the criteria against which the Hybrid-DSP is assessed in Section 4.8.2 and further discussed in Chapter 6.

Table 4.4: Design criteria for the development of the Hybrid-DSP developed from themes from multiple sources of data

Design criteria for Hybrid-DSP	Sources of evidence
Approach to its use:	
Integrated across multiple aspects of a decision problem	WFD: Preamble [7,9,26] WFD WG 1:highlighted need to incorporate a wider range of drivers for investment
Participatory approach to decision making	WFD: Preamble [14], Article 14; EC (2003h) INT 8; Observations by researcher: WFD WG requiring more engagement in structured understanding of the problem domain.
Can facilitate local decision maker engagement	WFD: Preamble [13] "*Decisions should be taken as close as possible to the locations where water is affected or used*." Observation: local knowledge on risks to the catchment and hence potable water supply could be incorporated into the decision support process (similar to the DWSP process).
Easy to apply/ use /intuitive	Turban *et al*. (2007); INT 5 [ID70,ID73], INT6 [ID09], INT 7 [ID 31], INT 8 [ID 34];
Use common language	Turban *et al*. (2007) ; INT 5 [ID70,ID73], INT 6[ID09]
User friendly operational interface	Turban *et al*. (2007); INT 5 [ID70,ID73],
Performance:	
Causal links between pressures and states and impacts	WFD (e.g. DPSIR framework, EC, 2003c); researcher observations of RG meetings; INT 3 [ID31]
Include different disciplines of information	RG 1,2,3; Observation: Wide range of inter-related factors affect potable water resources, including regulatory (Ofwat decisions), legislative (WFD, PoMs), physical (environment) and technological (WTW).
Include WFD issues	IM 1 & IM 10, IM37 [ID34], IM39 [ID22] ; WFD WG 1: classification of water bodies, and hence associated management measures need to be identified.
Acceptability of DSP with the regulators (Ofwat/EA/DWI)	INT 5 [ID70, ID73]
Clear assumptions, Robust and defendable	INT 5 [ID70,ID73], INT 8 [ID 34];
Guidance notes required for consistent application	INT 8 [ID 34], [ID 9].
Promote understanding of the WFD	INT 8 [ID 34]; Observation: WFD WG meetings.

Design criteria for Hybrid-DSP	**Sources of evidence**
Generate options for investment	INT 5 [ID 70, ID73]; RG 4, RG 5, RG 6
Conducts scenario testing	INT 5 [ID 70, ID73]; RG 4, RG 5, RG 6
Identification of important stakeholders	RG2, RG 3
Understand change with time	INT 8 [ID 34]; Observation: temporal change is present across the physical and political domains which affect potable water management.
Integration:	
Use confidence grades for information used the same as June Return data.	RG5 [ID31, ID70]
Integration with existing systems	INT 5 [ID70,ID73], INT6 [ID09], RG 5
Regulation, water resources and investment management ownership/ end-users	INT 7 [ID 31], INT 8 [ID 34]; FG 1,2,3.

4.5 Selection of techniques

To respond to the dynamic problem domain tools and techniques were incrementally identified and applied, in order to address RQ 3.2. The strategic nature of the problem domain and the associated dynamic and inter-dependent factors, demanded an approach which was flexible and could be adapted with new information. Within the literature Bayesian networks were initially identified as an emerging technique which was and still is being researched for water resource management in response to the recent WFD implementation. The technique has been favoured due to its recent success in offering an integrated and a participatory approach for decision making in WRM, as discussed in Chapter 2. Specifically the technique has also been used to assess the implications of measures being brought in through the WFD to manage point and diffuse sources (e.g. Barton *et al.*, 2005). Therefore this contemporary support for the use of BNs within WRM and assessing the implications of the WFD presented a strong case for their selection, and consequent basis for the developed Hybrid-DSP.

However, during applications of BNs developed by both the researcher and with feedback from the water company (during reference group meetings, informal discussions and observations made by the researcher of participants, as discussed in Section 4.6), the nature of the variables and their inter-relationships were difficult to identify. Therefore further methods to characterise the uncertain and complex issues within the problem domain (e.g. feedback from draft RBMPs, new PoMs, new Directives, incidents affecting drinking water supplies [water quality exceedances in metaldehyde, clopyralid and cryptosporidum during 2008]) were recognised by the researcher to be required, to promote organisational understanding of the problem and potential organisational responses. Additional techniques to characterise the nature of the variables and the identification of their causal relationships, as well as a method to establish who the associated influential stakeholders affecting the problem domain, were required. Therefore an assessment of the integrated nature of the complex and uncertain problem domain could be conducted, to identify how and in what way the WFD would impact on the management of potable water supplies. Once these contextual relationships are known, further quantitative analysis of the impact of the factors could then be conducted using probabilities within BNs.

The following qualitative techniques were selected by the researcher to be suitable for the problem domain within this research, based on a review of strategic methods for understanding the uncertain external environment.

- Strategic analysis using: PESTEL and SWOT analysis frameworks, together with resource and capability analysis.
- Potable water supply system analysis
- Stakeholder analysis
- Causal analysis using: Bayesian networks and DPSIR framework

A summary of the techniques, their references, and justification is provided in Table 4.5. The following sections discuss the use of BNs together with the combination of additional strategic analysis techniques resulting in a Hybrid-DSP. The resultant Hybrid-DSP is presented in Section 4.8.

Table 4.5: Summary table of the selection of methods for inclusion in the Hybrid-DSP, the source of data used as an input for the method, and the sources of feedback for the use of the methods

Method	**Justification for use** *(evidence from case study organisation/ literature/ benefits of the method).*	**Use of method/ technique**	**Feedback on the method**	**Method reference**
BN (Bayesian Network)	Based on academic literature reviewed (Chapter 2) and a review of the requirements of the organisation. Main features include i) incorporates uncertainty, ii) flexible and includes new information and variables, iii) can be used in a participatory way, iv) can promote organisational learning.	Throughout the research during 2007-2010, during RG mtgs 3-9, INTs (2009).	Semi-structured interviews (ID31,34, Sept 2008) Semi-structured interviews (Sept 2009 –ID9, ID70, ID73) Reference Group meetings (No. 3,4,5,6,7,8,9) Focus Group meetings (FG1,2,3) WFD WG (03/03/2008) WFD WG (13/03/2009)	Jensen, 2001; Kjaerulff and Madsen., 2008; Bromley, 2005.
PESTEL (Political, Economic, Social, Technological, Environmental, Legal)	Based on researcher observation of the organisation there appeared to be limited characterisation of strategic issues impacting on water resource management. Based on review of the organisational processes and systems which highlighted limited integration of multiple aspects of the problem domain. PESTEL is a recognised technique to assess the strategic challenges facing an organisation.	Semi-structured interviews (INT 1 – 4 in Sept 2008), discussed in RG 4 and 5.	During semi-structured interviews (INTs 1-4 in Sept 2008) Reference Group 6, Focus group 1,2 and 3 for integration of the Hybrid-DSP. Feedback during WFD WG (13/03/2009)	Luffman *et al.*, 1996; Johnson *et al.*, 2008; Kew and Stredwick, 2005.
Potable water supply system assessment.	Identify impacts of the WFD across the potable water supply system, to characterise how and when the WFD may impact on the system and what specific implications need to be understood. This approach supports the Davidson *et al* (2005) approach to identifying risks to potable water supply and integrates with the internal organisational DWSP approach.	Demonstrated in RG 8, reviewed in INT 5, and FG 1,2 and 3	RG 8, INT 5, and FG 1, 2 and 3	General system view of potable water supply. Informed from Davison *et al.*, (2005). Codes selected to analyse the related impacts on the potable water supply system.

Method	**Justification for use** *(evidence from case study organisation/ literature/ benefits of the method).*	**Use of method/ technique**	**Feedback on the method**	**Method reference**
SWOT (Strengths, Weaknesses, Opportunities, Threats).	Observations of the organisation identifying investment responses in a piecemeal meal, through responses to regulatory requirements (e.g. PoMs) highlighted a broader review of the threats and opportunities which the organisation faced in relation to the WFD and other strategic drivers. Hence wider identification of organisational responses to the changes in the external environment could be identified in line with those required for the WFD, hence to contribute to an alignment in strategy development. SWOT is a recognised strategic analysis framework to support strategy development.	During questions and discussion in semi-structured interviews (Sept 2008, 2009)	Informed from general discussion in reference group meetings, and focus groups for integration of the Hybrid-DSP.	Luffman *et al.*, 1996, Kew and Stredwick, 2005, Johnson *et al.*, 2008.
DPSIR (Driving Force, Pressure, State, Impact, Response)	Using BNs indicated an understanding of the causal relationships between variables needed to be further understood to be able develop more informed BNs. Multiple developments in the strategic environment (e.g. a new Groundwater Directive, Nitrates Directive and the WFD, all identifying interventions to control pollution) needed to be understood to identify both singular and collective impacts on the potable water supply system. DPSIR is a recognised causal framework which can be used to understand the links between factors to inform management responses (Smeets and Weterings, 1999). DPSIR is advocated through the development of the RBMP and PoM identification (EC, 2003c)	Semi-structured interviews (Sept 2009 ID70, ID73, ID9)	Reference group meetings, Focus group for integration of the Hybrid-DSP	Smeets and Weterings, 1999; La Jeunesse *et al.*, 2003; Elliott, 2002; Cave *et al.*, 2003; Petersson *et al.*, 2007; Agyemand *et al.*, 2007, EC, 2003c.

Method	**Justification for use** *(evidence from case study organisation/ literature/ benefits of the method).*	**Use of method/ technique**	**Feedback on the method**	**Method reference**
Stakeholder Analysis	Observation by the researcher during RG 1, 2 3, 4, 5 that water managers did not understand the stakeholders who have an influence on the management of the wider environment regarding the management of the catchment. The importance of understanding the level of interest or influence which stakeholders have, would inform the level effectiveness of the stakeholders in the implementation of any associated measure addressing pollution control. The method would also provide a basis for identification of strategic partners to build relationships with to manage diffuse and point source pollution affecting potable water sources. This would contribute towards improving the effectiveness of implementation measures. Stakeholder analysis is a recognised method to conduct an assessment of the influential stakeholders affecting a specific issue.	Reference group meeting (RG 6) with workshop activity August 2008.	Reference group meetings 5,6. Focus group for integration of the Hybrid-DSP (FG 1,2,3). WFD WG (13/03/2009)	Johnson *et al*, 2008; Reed *et al*, 2009.
Resource and capability assessment	Observation by the researcher in the development of organisational strategy in both the AWS WFD WG meetings, and comments made by ID73 (09/09/2009) interview regarding the need to identify how to implement catchment management (now obtained funding from Ofwat). Also identified from the water managers in the reference group, that only technical responses to problems had previously been identified, whereas the WFD requires a wider range of responses to be considered by the organisation. Technique is a recognised approach for identifying and analysing strategies (Grant, 2008).	Researcher used the approach, informed from observations of the water company.	Discussions in reference group meetings and focus groups (1-3), regarding what resources and capabilities needed to be developed for both organisational responses to the WFD, and to use the Hybrid-DSP.	Informed from Grant, (2005); Grant, (2010)

4.6 Decision support using BN

The selection of Bayesian networks for use within the Hybrid-DSP was identified in Section 4.5, which was supported by evidence from the review conducted in Chapter 2. This section focuses on the suitability of BNs for use within a UK water company to manage potable water supplies, addressing both the practical and technical issues of their application. Further development of the use of BNs is subsequently presented through the coupling with other techniques explored in this chapter (see Section 4.7) which culminate in the development of a Hybrid-DSP in Section 4.8.

4.6.1 Approach to BN construction

Throughout the research BNs have been progressively constructed using guidelines adapted from the work of Bromley (2005). The seven stages for development were: 1) the definition of the problem and selection of an appropriate spatial and temporal approach, 2) identification of variables, possible actions and indicators adequate for evaluating the different management options, 3) design of a preliminary network to be used as a basis for discussion, 4) data collection, 5) definition of the states of variables, 6) construction of the conditional probability tables, and, 7) validation of the network with the stakeholders. The design of BNs were developed between 2008 and 2010, with variations in: the type of BNs (e.g. Influence Diagram, Dynamic BNs, Object Orientated BNs); the variables included (single groundwater source, multiple groundwater sources, water quality and quantity aspects); and variations in the states of variables (e.g. Boolean, intervals). These combinations reflected new information obtained as well as an improved understanding of the problem domain. An overview of the activities undertaken to support BN development during the reference group meetings are provided in Table 4.6, and further discussed in the subsequent sections.

Table 4.6: Summary of the RG meetings and activities related to BN development

RG meeting	Date	Purpose	Activities
RG1	03102006	Introduce project and problem definition.	Set up reference group and roles.
RG2	11/01/2007	Introduction and identification of organisational processes and resources available.	Discussed organisational developments and decision support processes. Identified further contacts in the organisation and sources of data.
RG3	12/02/2008	Select case study to use as a basis to develop Hybrid-DSP focused on understanding the WFD impact on WTW.	Discussed WFD impacts, and potential case study sites to be used. Case study site selected.
RG4	15/05/2008	Selection and introduction of BN methodology.	Introduce BN method and engage in discussion with reference group members regarding its use and suitability
RG5	13/08/2008	BN application to GW nitrate case study.	Initial BNs presented and discussed in the reference group
RG6	19/12/2008	Further BN development to case study.	Presented further models of BN to the group. Highlighted the use of OOBN to incorporate specific components of the model within the organisation. Illustrated how BN would be integrated within the organisation with the existing systems.
RG7	23/04/2009	Present BN model developments and Hybrid-DSP design	Further BN models were presented and discussed, and integrated with other methods to form a Hybrid-DSP.
RG8	26/08/2009	To present research undertaken on the WFD, and to demonstrate the Hybrid-DSP.	Presented with a demonstration the Hybrid-DSP for further comment/ feedback.
RG9	06/01/2010	Collectively identify the integration of the proposed approach within the water company.	Discussion focused on integration of the Hybrid-DSP with the business with Asset Plus+ and ‘Risk and Value’.

BN applications were trialled to demonstrate the technique and involved the researcher identifying the variables, establishing the causal links, and populating the CPTs based on informed judgement and empirical data sources. During Reference Group 4, 5, 6, 7 & 8, as well as during semi-structured interviews (INT5 [ID70, ID73], and INT6 [ID9]) BNs were presented for discussion, to promote learning and understanding of the relationships between the variables and the outcomes of the use of BNs to inform decision making. The CPTs were developed by the researcher, together with examples of BNs and associated CPTs presented to the reference group for discussion. BNs with only a few variables (e.g. up to 15 variables), alongside BNs with a greater number of variables (e.g. >15) were developed, to explore and demonstrate their suitability for application within the context of this research. Further to this the development of the BNs into an Influence Diagram, through the incorporation of utility nodes, was also conducted to investigate the utility of alternative decision options (RG6). The following sections discuss the approaches taken for the construction of the BNs.

4.6.2 BN problem domain context and variable identification

During Section 4.3 the problem domain and case study selected for the development of the Hybrid-DSP were introduced. The case study of Barrow WTW was selected, and formed the basis for the development of BNs to understand the implications of the WFD on the management of potable water supply. Therefore the variables to be incorporated in the BNs, were based on those presented previously in the conceptual diagrams in Figure 4.1, Figure 4.2 and Figure 4.3. As identified by the researcher and through the reference group meetings, the spatial scale selected for the problem domain focused on the catchment surrounding the source. The temporal dimension included the impact of the WFD on the five yearly asset management plan (AMP), as well as the subsequent six yearly river basin management plan (RBMP) developments. The implications for future water treatment requirements, resulting from the changes in the raw water used for supply, were the focus of the output of the BN as a decision support tool.

The use of BNs to address this problem context serves multiple purposes. The variables identified in Figure 4.1, Figure 4.2 and Figure 4.3 can be integrated and hence inform an understanding of the causal relationships between the changes in one variable (e.g. the introduction of a measure to control diffuse pollution to farmland) and another (e.g. water quality of the water source). Through the development of the BNs, uncertainty in relation to the states and relationships between variables can also be represented. Hence as data becomes available the probabilities across the BNs can be updated to reduce the uncertainty associated with the causal relationships. Therefore, uncertainty in the decisions made in relation to the problem domain can be reduced.

During a period of rapid developments within the UK water industry, especially during 2008-09, the development of BNs and the associated variables to be included presented a challenge for the researcher and water managers. Identifying the appropriate management interventions and maintaining awareness of WFD developments were demanding. This was especially so when the organisational strategy for catchment management was being developed alongside the development of BNs, combined with national changes in the reclassification of Nitrate Vulnerable Zones and the extension of designated Catchment Sensitive Farming areas. However, BNs were able to accommodate these changes in the variables within the problem domain being modelled, due to the flexibility in the modification of BN design using software. During this process, it became evident to the researcher that a more structured process was required in order to facilitate the identification and documentation of variable selection or removal, as changes occurred within the problem domain. These aspects were further addressed through the additional techniques as identified in Section 4.7.

4.6.3 BN structure development

A range of networks to represent the problem domain were constructed by the researcher using information and data obtained from grey literature, organisational documents, and information from water company representatives. These BNs were discussed with the reference group (during RG 4,5,6 and 7) where modifications to the BNs were suggested and incorporated in further revisions of the BNs. In addition, network structures were also reviewed by individuals within the organisation during semi-structured interviews (INT 4, INT 5, INT 6) and informant discussions (IM46, IM53). Those involved included environmental regulation managers, water resource managers, asset managers, and a biosolids manager. The problem domain was initially represented by BNs, which were also developed to incorporate decision and utility nodes, becoming an Influence Diagrams (ID). In further representations of the problem domain, the impact of changes in the external variables in successive time steps were incorporated within a dynamic BN (DBN) and additional Object Orientated BN (OOBN) were demonstrated to incorporate multiple sub-sections of a BN. These variants of BN structures were all presented within the RG meetings and discussed with the reference group. The number of variables included in the BNs also varied, with BNs including many variables (i.e. complex BNs) as well as more parsimonious BNs which included only a limited range of variables being developed. Using a parsimonious approach was more beneficial, which reduced the extent of data to be collected for the subsequent population of the CPTs. Hence, only the main influential variables were included in further BN development.

Water managers found the visual representation of the structure of the BNs representing the problem domain intuitive, and that they provided a greater understanding of the integration of the multiple factors involved. Through successive meetings and discussions the reference groups' awareness of the potential to represent the multiple influences impacting on the problem domain enhanced cross-departmental understanding. Using the BNs as a visual framework for the basis of discussion, reference group members were able to exchange information and perspectives of the development of the WFD and how they perceived it to impact on the management of potable water resources.

4.6.4 Sources of data to inform BN applications

Multiple sources of qualitative and quantitative data were collected to inform the construction of the BNs. The sources included grey literature, legal documents, organisational documents (e.g. water treatment works manuals), site visits, semi-structured interviews, and informant discussions, which were identified within Section 3.6.1. These data collection activities took place between 2006 and 2010. The specific data sources used to inform BN applications for the site specific case study location are listed in Table 4.7. In using multiple sources of data, water managers recognised the value of using BNs to support decision making and enhance their understanding of the wider integration of variables. However, managers recognised that transparency in the sources of data used and the associated uncertainty of the data, should be maintained to satisfy regulators (e.g. Ofwat) (see Section 4.7.5).

Table 4.7: Summary of data sources used to inform BN applications

Type of information	**Sources used**
Case study site details	WTW manual (AWS, 2007b); informant discussions; site visits; Site specific CRAGs document (AWS, 2008b); Crystal QD warehouse (for nitrate concentrations in GW), HOST (hydrology of soil types); Drinking Water Safety Plan (including the hazard and control templates) (AWS, 2008c); Geographical and land use maps (EA, 2009b; Defra, 2009)
WFD implications	Humber RBMP (EA, 2009b); Humber PoMs in the Humber RBMP (EA, 2009b); Informant discussions.
Management actions	Humber RBMP (EA, 2009b); Humber PoMs in the Humber RBMP (EA, 2009b); Water Company Asset Management Plan (AMP5) PR09 (AWS, 2009a); water company catchment management strategy (cost data for workshops and agronomists) (AWS, 2008d); site visit to Wessex Water to explore nitrate management options; water company Strategic Direction Statement 2010-2035 (AWS, 2007a).
Legal compliance information	Water Framework Directive (2000/60/EC), Nitrate Directive (91/676/EEC), Groundwater Directive (2006/118/EC); Drinking Water Directive (98/83/EC); Nitrates Pollution Prevention Regulations (2008); Water Supply (Water Quality) Regulations Amendment (2007).

4.6.5 Definitions of states of variables and CPT construction

Once the variables to be included in the BNs were determined, the definition of the states of variables and the construction of CPTs were conducted principally by the researcher. Information from sources identified in Table 4.7 to inform the states of variables and the CPTs, were presented to the reference group for discussion, as well as during INT5 [ID70, ID73], and INT6 [ID9]). Where data was not available a conversion scale was used to translate ‘statements’ to probabilities (Kjaerulff and Madsen, 2008).

Water managers found the use of probabilities to represent relationships through CPTs challenging, as they were not used to thinking about values or relationships in terms of probabilities. This was evident during the reference group meetings where BNs were discussed (RG 4, 5,6 and 7), although as the understanding of BNs improved, managers became more accepting of the use of probabilities to inform decision making. The use of the probability conversion scale was presented and discussed during INT 5(ID70 and ID73) which was understood and accepted as a mechanism to inform CPTs when no information is available. Overall, the water managers recognised the value of using BNs to represent the relationships between the variables, even though the determination of probabilities may be challenging.

4.6.6 Management options and scenario modelling

The BNs developed incorporated different management options. The options incorporated included for example: investments in treatment technology (ion exchange), and catchment management (e.g. including agronomist advisors and the delivery of education and awareness workshops with stakeholders). These alternative investment options were modelled using both BNs and Influence Diagrams (IDs). Therefore the investment options were able to be evaluated using the probability of the state of an output variable (e.g. raw water quality), whilst the IDs could incorporate a measure of utility associated with the decision options selected. The use of scenarios within the BNs and IDs were regarded as a beneficial function of the technique by water managers. In using the scenarios, managers could understand the potential impact of the different management interventions on the selected output variables. In addition the use of the technique to inform investment options when a specific state of an output variable is instantiated, provided greater insight into the potential management options which would be suitable for a specific site.

4.6.7 Validation of BN

Due to the problem domain being focused on the future implementation of legislation, data to validate the management interventions were not available. Instead the development of the BNs were discussed openly within the reference group meetings during which the participants were able to challenge the representation of the problem domain within the BNs. It was accepted that verification of the BNs would be through their performance in reflecting what would be expected within the problem domain. However, as data becomes available through the implementation of the WFD, CPTs should be updated to reflect the most current understanding of the relationships between variables at specific sites.

4.7 Coupling of methods with BN

Although BNs have been identified through this research to be a valuable means of visualising the problem domain and understanding the impact of management interventions, their use in association with other techniques was found to be beneficial. In Section 4.5, approaches to structuring the factors which influence the problem domain were identified, as well as techniques to identify significant stakeholders, and potential investment options. This section further discusses the use and coupling of these techniques and how they inform BN construction, application and integration within the water company. Therefore, this section further contributes to answering RQ 3.2.

4.7.1 PESTEL framework

The limited understanding by the organisation of the nature of the factors which are influencing the management of water resources became apparent during early reference group meetings and informal discussions. A wide range of factors were identified, although there was no structured approach to their identification, hence no transparent process through which factors could be identified and assessed. Therefore, the adoption of the strategic assessment framework, PESTEL (e.g. Johnson *et al*. 2008), provided a structure through which the identification and prioritisation of strategic factors and stakeholders could be managed. During semi-structured interviews with water managers (INT 1-4) the PESTEL framework was explored. It was evident from these interviews that they emphasised different factors (e.g. political, economic, social, technological, environmental, and legal) dependent on their job function. The use of the framework with managers was also beneficial in capturing and developing organisational understanding of the wider strategic environment, whilst taking managers outside of the normal constraints of their job function. Hence the framework encouraged broader thinking of the issues to be understood for water management and the impact of the WFD implementation. During discussions in the interviews, the interviewees also elaborated on the factors identified, and started to make causal associations between the factors, whilst also identifying stakeholder groups associated with the factors. This was an important observation by the researcher, which promoted the selection of further techniques to identify and analyse the influence of relevant stakeholders (see Section 4.7.2) as well as the use of a causal framework for linking the factors: DPSIR (see Section 4.7.3). Therefore, in using the PESTEL framework the selection of variables for analysis within the BNs could be informed in a systematic way. Using the results from the interviews, and further identified factors by the researcher, this technique and the results have been represented in Section 5.3.1.

4.7.2 Stakeholder Analysis

Through the WFD implementation, specifically the development of the PoM, multiple stakeholder groups were identified as having different responsibilities for the implementation of the PoMs. It was evident through the researcher observations of WFD WG 1,2,3, and 4, and reference group meetings, that an appreciation of the role, responsibilities and spheres of influence of other stakeholder groups was limited within the company. In addition discussions with other informants from outside the water company (ID28, ID47, ID56, ID57, ID72) also highlighted the importance of having a greater understanding of the interrelationships between various stakeholders and their influence on the management of water resources. Through the use of BNs, the probability of stakeholders (e.g. farmers) actually implementing the PoMs was discussed. The uncertainty of the level of interest or influence of these relevant stakeholders, and hence their likelihood of implementing PoMs prompted the selection of a stakeholder analysis to further inform and raise awareness of water managers of these stakeholders. During RG6 a stakeholder analysis was conducted, to establish from the perspective of the water managers which stakeholders they perceived to be interested and who have influence in the implementation of the WFD and its impact on the management of nitrate in groundwater. In using the technique adapted from Reed *et al*. (2009), stakeholders were identified by the water managers. The process of identifying stakeholders thorough a facilitated discussion allowed for a greater understanding of the stakeholders related to the implementation of the WFD and their relationship to the management of nitrate in GW. The results from this exercise have been used as the basis for the stakeholder analysis presented in Section 5.3.1 and 5.4.3.

Feedback from water managers during the stakeholder analysis exercise (in RG 6), highlighted it was a beneficial technique to use to understand the relative positions of the stakeholders. Potential organisational responses, to improve the management of potable water supplies, were identified by managers which included how to develop more effective strategic relationships with the influential stakeholders. These responses are further developed in Section 5.3.2.

4.7.3 DPSIR framework

To promote the development of causal analysis between factors, (as identified in Section 4.7.1) and hence to further structure the factors for potential inclusion within a BN, the DPSIR framework was used. The Driving forces–Pressures-State–Impact and Response (DPSIR) framework enabled causal relationships to be developed between the factors identified through the PESTEL analysis. The classifications of the DPSIR factors were discussed with water managers during reference group meetings and during interview INT 5 [ID70,ID73] (09/09/2009). Although the terminology was considered to be confusing by water managers (e.g. the difference between a Driving force and a Pressure) the approach was regarded as useful. In using the DPSIR framework, specific 'Responses' could be targeted at different points within the D-P-S-I causal chain. In conjunction with the PESTEL framework, the type of 'Response' could also be explored, where social or technological 'Responses' were discussed with managers, in relation to the management of the 'State' of nitrate in GW. Hence an overview of the range of 'Response' options targeting different aspects of the causal chain could be systematically identified. The use of this causal framework was also found by the researcher to be helpful during the construction of the BN structures.

4.7.4 Analysis of organisational resources and capabilities.

Throughout the research, the organisational developments in response to the WFD were observed during WFD WG (1,2,3 and 4) to be incremental, being guided by EA requirements (e.g. observations of WFD WG 1,2,3 and 4). The changes being brought about by the WFD required a change in the nature of resources and capabilities held within a company. These changes included development of knowledge on new legislation (e.g. WFD, GWD), integrated water resource management, improved communications internally and externally, management of data regarding water resources, development of new roles and team structures, whilst also developing a new catchment management strategy. The analysis of the organisation in response to the changes in the external environment through the use of a SWOT analysis, and resource and capability assessment coupled together, could facilitate a structured approach to the identification of strategic response options. Hence, these responses could further inform organisational strategy development in response to the WFD. In using such a process, a more systematic approach to the identification of organisational responses to inform either a general organisational strategy or site specific response to a specific problem could be developed. These organisational response could then be incorporated into a BNs for detailed assessment to understand the impact of the identified response on the management of a specific problem (e.g. nitrate in GW). Although not fully implemented in collaboration with the managers, these analytical steps were regarded as useful to be incorporated within the Hybrid-DSP (in Section 4.8), and hence to inform the management options to be selected for inclusion in the development of BNs.

4.7.5 Uncertainty classification of data sources

Uncertainty in the data sources used to inform the methods was identified by water managers within RG 6 who requested alignment with the confidence grades used by the economic regulator Ofwat for justification of proposed investment. The confidence grades used within the 'June Return', (an economic regulatory requirement by Ofwat), are considered to represent the level of uncertainty regarding the source of the information used to identify the investment requirements. The grades are used by water companies, to provide a reasoned basis for companies to identify the reliability and accuracy of the data used to justify and represent their performance. The grades are determined based on a qualitative reliability band from A to D (Table 4.8) and accuracy bands 1 to 6 (and additionally X) (Table 4.9).

Table 4.8: June Return Confidence Grades (Ofwat, 2010b)

Reliability band	Description
A	Sound textual records, procedures, investigations or analysis properly documented and recognised as the best method of assessment.
B	As A, but with minor shortcomings. Examples include old assessment, some missing documentation, some reliance on unconfirmed reports, some use of extrapolation.
C	Extrapolation from limited sample for which Grade A or B data is available.
D	Unconfirmed verbal reports, cursory inspections or analysis.

Table 4.9: June Return Accuracy bands (Ofwat, 2010b)

Accuracy band	Accuracy to or within +/-	But outside +/-
1	1%	-
2	5%	1
3	10%	5%
4	25%	10%
5	50%	25%
6	100%	50%
X	Accuracy outside +/- 100 %, small numbers or otherwise incompatible.	

Confidence grades of A2, A3, B2 or better are expected by Ofwat. Where these grades are not achievable action plans to address these are required. If only A4, B3, B4, or C2 are achievable, these should be justified, and where appropriate further identification of investment to increase the confidence in the data used. These categorises should be used to inform the data used within the BN.

With regard to the data used for the construction of BNs, Cain (2001) also identified a categorisation scheme, to record the nature of the data used to inform the development of BNs (Table 4.10). These definitions are considered by the researcher to be useful alongside those from Ofwat to record in more detail the nature of the information and data used to inform the development of BNs. Table 4.10 provides an overview of the type of information sources used by Cain (2001) where Type 1 data is preferable to Type 4, although where insufficient data is available Type 4 is appropriate.

Table 4.10: Data types for use in BN probability determination (Cain 2001, p.51)

Data type	Description
Type 1	Raw data collected by direct measurement
Type 2	Raw data collected through stakeholder elicitation
Type 3	Output from process-based models calibrated using raw data collected by direct measurement.
Type 4	Academic “expert” opinion based on theoretical calculation or best judgement.

4.8 The Hybrid-DSP

The previous sections have presented the use of BNs to address the problem domain, in addition to the coupling of BNs with other strategic management techniques. This section presents the Hybrid-DSP both the initial version (Figure 4.4) and a more refined version (Figure 4.5) which has more detailed steps. These details have been informed from the incremental and iterative application of the methods with water company representatives, whilst also receiving feedback on their use in response to the requirements of the water company. The combined methods within the Hybrid-DSP allow for the characterisation of the problem domain, and hence the reduction in contextual uncertainty, whilst also providing an interactive learning process within the water company. Hence, these combined features contribute towards the development of internal capacity to understand the problem domain, and progressively develop informed investment options for the management of potable water supplies.

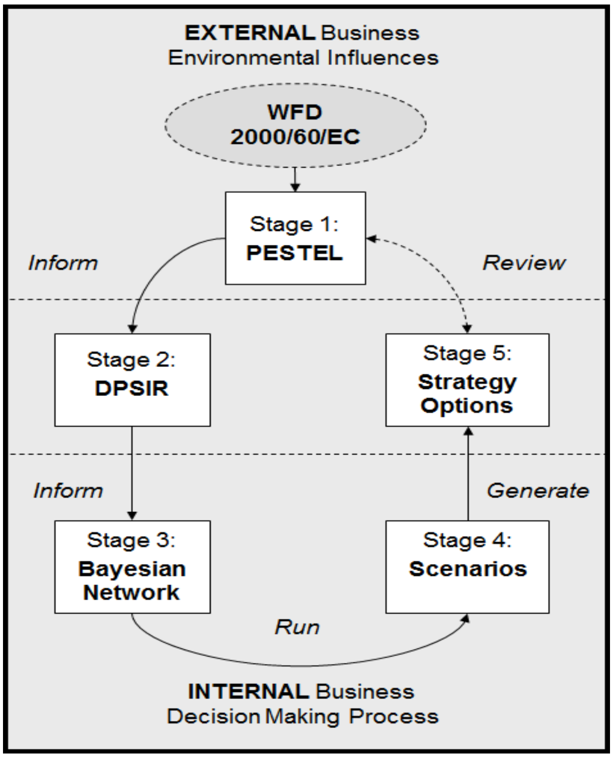


Figure 4.4: Unrefined Hybrid-DSP

Figure 4.4 illustrates the simple version of the Hybrid-DSP, which was discussed with the water company during the conduct of the research, and presented at WFD WG 4, as well as at Reference Group 7 and 8 and Focus Group 1,2 and 3. The value of the use of existing tools and techniques is recognised in their integration with each other. Through the successive application of the methods and tools the contextual uncertainty related to the problem domain is reduced. Prioritisation of the factors identified using PESTEL and further causal analysis using the DPSIR framework, allows for the narrowing and targeting of factors to be analysed in more detail. Using only one method in isolation would only provide an increase in the knowledge associated with the specific technique and not provide an holistic assessment of the problem domain. The use of all the techniques as an holistic analytical process supports the decision maker in informing the development of potential strategic options for both strategic organisational level options and site specific options. The data used within the Hybrid-DSP and ultimately used in the construction of the BNs would be transparently represented in reporting the proposed investment options, and therefore enhancing the credibility of the approach with the regulatory stakeholders. The Hybrid-DSP as a facilitated process in a cross-departmental reference group, would consequently provide for enhanced organisational learning through knowledge sharing and contribute to increased developments in organisational capabilities to respond to the WFD. The refined Hybrid-DSP depicted in Figure 4.5, is divided into Phases 1 and 2, and Steps 1.1 to 2.17.

In addition, a Microsoft Excel 2010® 'workbook' was developed to capture and centralise the data management of the decision support process. The objective of this was to allow information to be transparently shared and recorded by the various stakeholders in the water company that needed to be engaged in the process. Example screenshots of the 'workbook' are provided in Figure 4.6 and Figure 4.7. The 'workbook' was designed to progressively capture the data and information obtained from each of the steps and hence allow for integration between the tools coupled within the Hybrid-DSP. For this reason, the 'workbook' allows for the data to be identified and refined through the course of the Hybrid-DSP implementation in an iterative process, resulting in the production of a large data set which can be referred to, developed and refined, depending on the specific problem domain or case study location to be studied. The 'workbook' comprises several spread-sheets, identifying the requirements of each of the individual tools within the Hybrid-DSP, with one overarching 'main sheet' which houses the output data from each of the various tools, and hence provides the central interface with which to manage the data.

The outputs from each step are summarised in Figure 4.8, and the process is described in detail in the accompanying implementation handbook in Appendix E. The full Hybrid-DSP is described in Chapter 5.

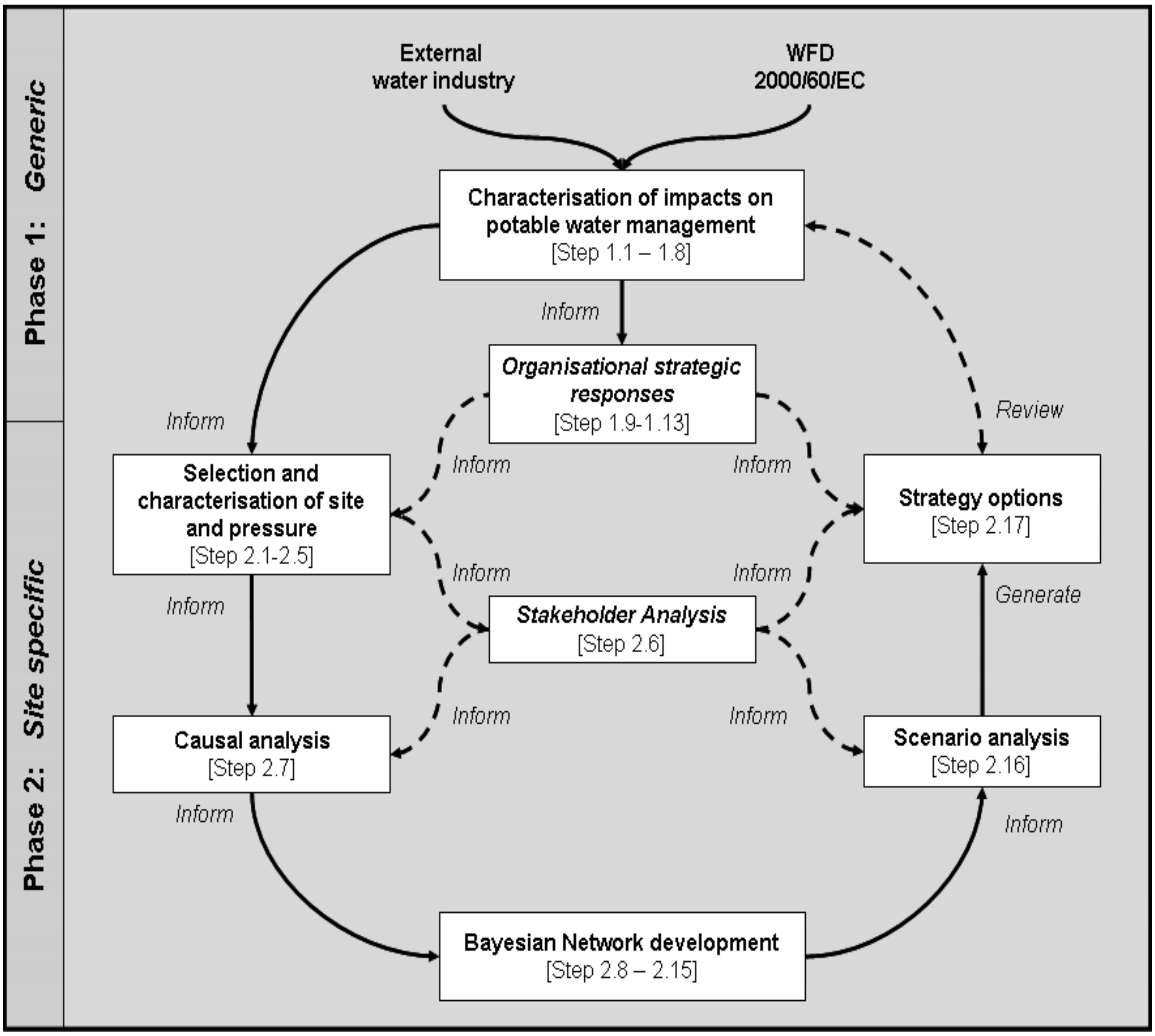
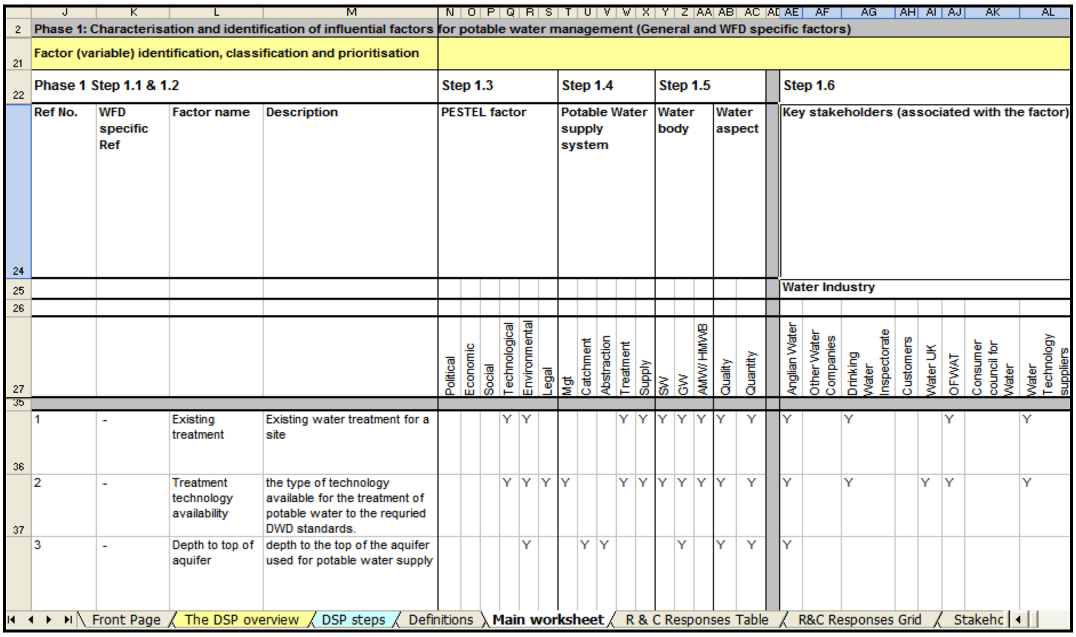


Figure 4.5: The Hybrid-Decision Support Process (Hybrid-DSP)



Phase 1: Characterisation and identification of influential factors for potable water management (General and WFD specific factors)																												
Factor (variable) identification, classification and prioritisation																												
Phase 1 Step 1.1 & 1.2				Step 1.3						Step 1.4					Step 1.5					Step 1.6								
Ref No.	WFD specific Ref	Factor name	Description	PESTEL factor						Potable Water supply system					Water body			Water aspect		Key stakeholders (associated with the factor)								
																				Water Industry								
				Political	Economic	Social	Technological	Environmental	Legal	Mgt	Catchment	Abstraction	Treatment	Supply	SW	GW	AMWV/HMWB	Quality	Quantity	Anglian Water	Other Water Companies	Drinking Water Inspectorate	Customers	Water UK	OFWAT	Consumer council for Water	Water Technology suppliers	
1	-	Existing treatment	Existing water treatment for a site				Y	Y					Y	Y	Y	Y	Y	Y	Y	Y		Y			Y		Y	
2	-	Treatment technology availability	the type of technology available for the treatment of potable water to the requried DWD standards.				Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y		Y		Y	Y		Y	
3	-	Depth to top of aquifer	depth to the top of the aquifer used for potable water supply					Y			Y	Y				Y		Y	Y	Y								

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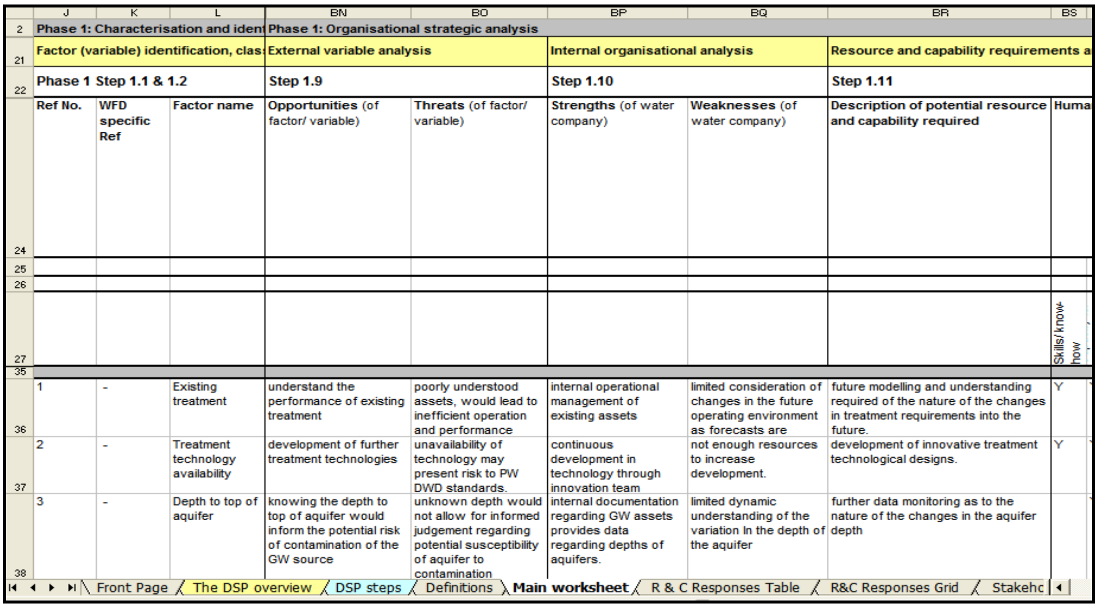
Figure 4.6: The Hybrid-DSP process steps 1.1 to 1.6



Phase 1: Characterisation and ident			Phase 1: Organisational strategic analysis					
Factor (variable) identification, clas			External variable analysis		Internal organisational analysis		Resource and capability requirements a	
Phase 1 Step 1.1 & 1.2			Step 1.9		Step 1.10		Step 1.11	
Ref No.	WFD specific Ref	Factor name	Opportunities (of factor/ variable)	Threats (of factor/ variable)	Strengths (of water company)	Weaknesses (of water company)	Description of potential resource and capability required	Huma
								Skills/ know-how
1	-	Existing treatment	understand the performance of existing treatment	poorly understood assets, would lead to inefficient operation and performance	internal operational management of existing assets	limited consideration of changes in the future operating environment as forecasts are	future modelling and understanding required of the nature of the changes in treatment requirements into the future.	Y
2	-	Treatment technology availability	development of further treatment technologies	unavailability of technology may present risk to PW DWD standards.	continuous development in technology through innovation team	not enough resources to increase development.	development of innovative treatment technological designs.	Y
3	-	Depth to top of aquifer	knowing the depth to top of aquifer would inform the potential risk of contamination of the GW source	unknown depth would not allow for informed judgement regarding potential susceptibility of aquifer to contamination	internal documentation regarding GW assets provides data regarding depths of aquifers.	limited dynamic understanding of the variation In the depth of the aquifer	further data monitoring as to the nature of the changes in the aquifer depth	

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Figure 4.7: The Hybrid-DSP process steps 1.9 to 1.11

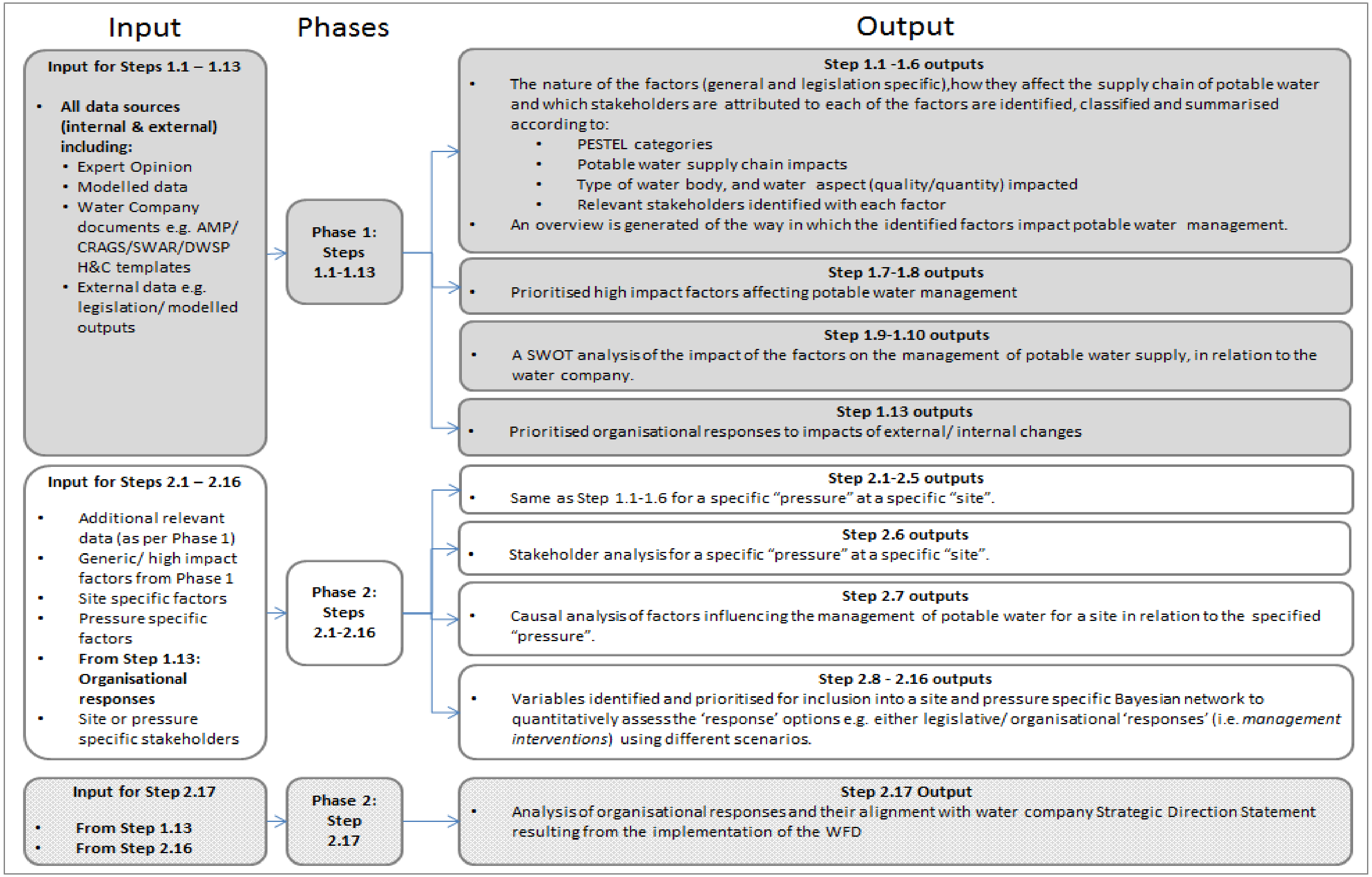

Figure 4.8: Overview of the inputs and outputs from the Hybrid-DSP

4.8.1 Hybrid-DSP implementation within the water company

The process and features for the integration and implementation of the Hybrid-DSP within the water company were identified in order to address RQ 3.4. The integration of the Hybrid-DSP with existing techniques within the organisation was identified, together with the roles and business units who would be responsible for implementation of the process. This was dependent on the organisational knowledge of the changes within the internal systems, as well as the changes within the departments and roles within the organisation. During the process of the development of the Hybrid-DSP and the iterative combination of the methods, integration requirements were cumulatively identified (RG 5, 6,7,8,9; FG 1,2 and 3), and resulted in three options: i) use in conjunction with the Drinking Water Safety Planning (DWSP) approach, ii) use to inform the first stage of the 'Risk and Value' process (R&V) and iii) updating pre- and post-position risks of service measure failure in Asset Plus+. In collaboration with the water company, managers determined the preferred option for the integration of the BN based Hybrid-DSP would be to directly inform the Asset Plus+ system. Through discussions during FG 1, 2 and 3 with water company asset managers as well as asset management consultants during FG 2 (see Table 3.7, Section 3.6.1), the output of BNs were identified as being suitable for updating the risk profile of site specific water treatment performance in relation to service measure failure within the Asset Plus+ investment management system (see Table 4.1, Section 4.4.1). Full integration with the water company was not achieved during the research period, although the process of how the output from the BNs could be integrated with Asset Plus+ was discussed in detail during FG 1 and 2 resulting in a proposed integration plan (Asset Management Consultants, 2009).

Through the integration process, changes in the quality of source water are therefore identified using the Hybrid-DSP. Hence, the impact of these changes on the performance of any existing assets can be determined through the use of BNs, to update the risk profile for the specific water treatment asset. Investment options of increased investment, no investment or delayed investment could therefore be generated in response to the impact of external events and changes in raw water quality used for potable water supply. Overall this is aimed at reducing the risk of failing customer service standards for the provision of potable water to customers, hence failure of industry service measures (e.g. interruptions to supply).

To achieve the integration of BNs as part of Asset Plus+, further development of the capability in the use of BNs within the water company to conduct site specific assessments is required. During FG 3, the Hybrid-DSP process was discussed and presented as a flexible approach to be conducted with managers from a cross-section of departments, for specific ‘pressures’ (e.g. nitrate/ pesticide) at specific sites. The business units involved and hence the ownership of the steps in the Hybrid-DSP, as well as the capabilities for each of the steps were identified collaboratively resulting in an implementation plan (this is combined within Appendix E). However, the development of the on-going capability in the use of BNs to support the Hybrid-DSP implementation had not been resolved within the timeframe of the research. Potential options discussed in FG3 included developing internal capability in the use of BNs (through training of existing personnel or through recruitment of additional in-house expertise) or utilising external consultants to undertake the BN development for specific sites.

4.8.2 Hybrid-DSP evaluation

An evaluation of the Hybrid-DSP against the design criteria identified in Section 4.4.3, is reported in Table 4.11. In addition organisational perspectives of the Hybrid-DSP and the component techniques are presented in Section 4.8.3.

Table 4.11: Hybrid-DSP evaluated against design criteria

Design criteria for Hybrid-DSP	**Met criteria?**	**Evaluation of the Hybrid-DSP**
Approach to its use:		
Provide integration of multiple aspects of a decision problem	✓	The use of the combined methods to identify factors and their selection for representation within the Bayesian Network facilitates integration across multiple aspects of the decision problem.
Participatory approach to decision making	✓	The use of the techniques during each of the steps allows for the participation and representation of water managers during the identification of the problem, the selection of variables, the identification of stakeholders and discussion regarding the development of the BNs for each site. The level of participation can be varied for each application, dependent on resources (people and time) available

Design criteria for Hybrid-DSP	**Met criteria?**	**Evaluation of the Hybrid-DSP**
Can facilitate local decision maker engagement	✓	The techniques can be used with local decision makers either to contribute to the process, or to present the outcomes of the techniques for discussion with local decision makers.
Easy to apply/ use /intuitive	-	Individual steps of the Hybrid-DSP would be easy to apply, although time needed to apply the process for multiple sites and conditions may be a limiting factor. Although visually intuitive, the development of the BN modelling element would need to be undertaken by a specialist
Use common language	-	Language and terms may be challenging due to the different categories used to classify the variables, as well as the terminology used in the BN modelling step.
User friendly operational interface	✓	Use of spreadsheet database is encouraged to ensure transparency in data management. BN visual interface is easy to understand.
Performance:		
Causal links between pressures and states and impacts	✓	Incorporation of DPSIR as part of the Hybrid-DSP and the BN facilitates the representation of causal linkage.
Include different disciplines of information	✓	Multiple disciplines are able to be included
Include WFD issues	✓	WFD measures can be included
Acceptability of Hybrid-DSP with the regulators (Ofwat/EA/DWI)	-	Initial developments of the use of BN with the EA (Chapter 2) highlights the understanding of the use of BN by the environmental regulator, although not fully recognised by regulators at present.
Clear assumptions, robust and defendable	✓	Assumptions regarding the identification, selection and incorporation of the variables into the BN based Hybrid-DSP should be recorded in a database.
Guidance notes required for consistent application	✓	An implementation guide book is provided in Appendix E
Promote understanding of the WFD	✓	The process of identifying factors, and characterising factors enhances organisational understanding of the implications of the WFD.
Generate options for investment	✓	Options for investment are generated through the SWOT and resource and capability analysis, which can be selected for further analysis to assess their impact on specific output variables, within a BN using scenario analysis.
Conducts scenario testing	✓	Scenario analysis is conducted through the BN.
Identification of important stakeholders	✓	Use of stakeholder identification and stakeholder analysis informs the water managers of the significant stakeholders to be engaged with to inform strategies for potable water management.
Understand change with time	✓	BN can be used dynamically to predict changes over time, although based on subjective expert opinion, unless data becomes available.
Integration and implementation		
Use confidence grades for information used the same as June Return data.	✓	Confidence grades have been incorporated into the classification of the uncertainty of data associated with each of the variables.
Integration with existing systems	✓	The output from the BN can be used to inform the pre and post investment position within the Asset Plus + investment management system, with further potential to be incorporated as part of the DWSP and the initial stages of the Risk and Value approach.
Regulation, water resources and investment management ownership/ end-users	✓	The Hybrid-DSP has been designed to be used across business units, although specific BN expertise was identified to be suitable to be located within the water resources team, as part of the catchment modelling role.
Note: ✓ = addressed criteria successfully, (-) = requires further work		

4.8.3 Organisational perspectives and responses

Throughout the development of the BN based Hybrid-DSP, as discussed in this Chapter, water managers provided their perspectives on the techniques through their use and through discussion of the results of their use. Additional perspectives were obtained from consultants who were involved in developing the integration of the Hybrid-DSP within the water company. Sections 4.6 and 4.7 discussed perspectives and responses of the water company managers alongside the application of the techniques which were observed by the researcher and are further detailed in this section. These perspectives offer valuable information on the usefulness of the BN based Hybrid-DSP as an approach to inform organisational decisions regarding potable water management in response to the WFD, and hence inform the response to RQ 4.1.

The use of BNs was perceived by water managers (ID34, ID59) and consultants (ID39 and ID45) to offer a potential mechanism to predict the future water quality in response to management measures to control pollution. BNs were recognised as being able to incorporate a wider range of influences affecting the management of groundwater. These multiple influences offer a greater degree of sensitivity in relation to water quality predictions. In light of this potential, the water managers recognised BNs could be used to inform and refine the values within Asset Plus+ in relation to the potential risk of future failure of potable water treatment technologies.

During the discussions regarding the development of BNs within RG 5,6,7 and 8, the BNs were perceived to be a useful technique to incorporate multiple factors, and assess the implications of the different management options. However, this perceived strength of the technique by ID 31, ID 34, ID 70, ID 73 during reference groups 4-8, was countered by the perceived complexity of the approach highlighted by ID59 in FG1. Despite this reservation, BNs were recognised by the water managers who had been more consistently involved in the research, to offer a technique which could be integrated with existing organisational processes (including the DWSP, the ‘Risk and Value’ process and the Asset Plus+ system), recognising that BNs offered a flexible approach in enhancing existing organisational decision making processes.

The complex and uncertain environment of future water quality, was recognised by ID34 to be similar to the conditions surrounding the management of water supply and demand. Hence, ID34 further alluded to the potential of BNs being used for the management of future water supply and demand, although this had not been covered specifically within this research.

Although initially BNs were considered to be applicable as a generic model for the whole region, due to the localised features affecting water resource management, site specific BNs would need to be developed. Site specific development was supported by ID 70 and ID73, although during FG 2, ID39 highlighted that the potential time required to design and implement multiple BNs for all the existing surface and groundwater sites may be a constraint to their full application. This was recognised during further elaboration of this issue in FG 2, as being a problem when modelling more than one water quality parameter (e.g. nitrate or pesticides).

The overall perception of the approach as recognised by an external consultant operating within asset management in the UK water industry (ID39), indicated the approach represented a new way of considering the impact of the WFD on the management of potable water resources; "*I think this is great stuff actually, I`m surprised at how much you`ve done, I don`t think 'Water Company C' have got this far with the WFD*".

5 Demonstration of the Hybrid-DSP

5.1 Overview

The proposed Hybrid-DSP developed in Chapter 4 is demonstrated within this Chapter to address Stage 6 of the Hybrid-DSP development (see Section 3.4.3). In doing so, this Chapter further supports the achievement of Objective 3 of the research (see Section 1.5). Both the generic (Phase 1) and site specific (Phase 2) factors influencing the management of potable water, as well as management interventions to control the influential factors are established. An assessment of the impact of these factors and responses on a specific case study site is made using BNs, which results in the identification of strategic organisational responses to manage potable water at both the generic organisational, and at the site specific level. The results from this demonstration are discussed within Chapter 6, together with the implications for the organisation.

5.2 Introduction

The Hybrid-DSP is demonstrated using the Barrow catchment as a case study which is concerned with nitrate contamination in groundwater used for potable supply. Phase 1 of the Hybrid-DSP identifies and analyses the generic factors affecting the management of potable water, whilst Phase 2 analyses the impact of a specific pressure (nitrate application to land) on the management of potable water resources in the Barrow catchment. Each of the steps in each Phase of the Hybrid-DSP (presented in Chapter 4, Figure 4.5) are introduced and applied sequentially within this chapter. Specific details for each step are provided in Appendix E. A Microsoft Excel 2010® 'Workbook' is used as a central database for the processing and management of information for the demonstration of the Hybrid-DSP. Within this Chapter, summary tables and figures are presented to show the outputs of the Hybrid-DSP. The data and information used within the Hybrid-DSP presented in this chapter is based on the information gathered during the development and trial of the individual approaches with the water company (as discussed in Chapter 4). Further information and judgement has been included by the researcher where the integration of the methods or additional data have been required.

Throughout this Chapter a range of terminology is introduced and is summarised here, however the full definition of terms used are provided in the glossary within the implementation handbook in Appendix E. ‘Factors’ refers to all issues/aspects/features identified during Step 1.1-1.8 and Step 2.1-2.5 which may affect the provision of potable water. During Step 1.9-1.13 and again in Step 2.7 ‘responses’ are identified. These are also referred to as management interventions, with the aim to address the impact the ‘factors’ may have on potable water supply. These ‘responses’ may include organisational ‘responses’, existing legislative ‘responses’ or new WFD ‘responses’. Once ‘factors’ and ‘responses’ are analysed and prioritised for selection to become part of a BN (Step 2.8-2.16), they are then collectively termed ‘variables’ in accordance with BN terminology.

5.3 Phase 1: Generic assessment

5.3.1 Characterisation of the factors and their impact on the provision of potable water (Step 1.1-1.8)

The identification of factors (both ‘general’ and ‘WFD specific’) (Step 1.1-1.2), the classification of factors as being political, economic, social, technological, environmental or legal (PESTEL) (Step 1.3), the level of the potable water supply chain they affect (Step 1.4), and the type (groundwater [GW], surface water [SW], artificial water body [AWB]/ heavily modified water body [HMWB]) and aspect (quality or quantity) of water they are concerned with (Step 1.5), together with the associated stakeholders for each factor (Step 1.6) were informed from multiple sources of data. These included discussions with reference group members throughout the period of the research, additional informant discussions with water company representatives, grey literature, academic literature, site visits, legislation and direct interpretation specifically of the WFD by the researcher. Examples of ‘general’ factors include raw water quality and water treatment type, whilst ‘WFD’ specific factors include specific references in each of the articles, for example: Article 4(1) (c) is concerned with the protection of potable water sources. These factors and their impact were then subjectively classified by the researcher (informed by evidence and data gathered during the research), as having high, medium or low impact on the provision of potable water (Step 1.7). Of these, the high impact factors were selected (Step 1.8) for further analysis in subsequent steps of the Hybrid-DSP. A quantitative representation of the characterisation of the high impact factors are presented in Figure 5.1, Figure 5.2, Figure 5.3 and Figure 5.4, which summarise the output from Steps 1.1-1.8. In total, 65 high impact factors were prioritised for further assessment, which included 34 ‘general’ and 31 ‘WFD’ factors, from 75 factors in total.

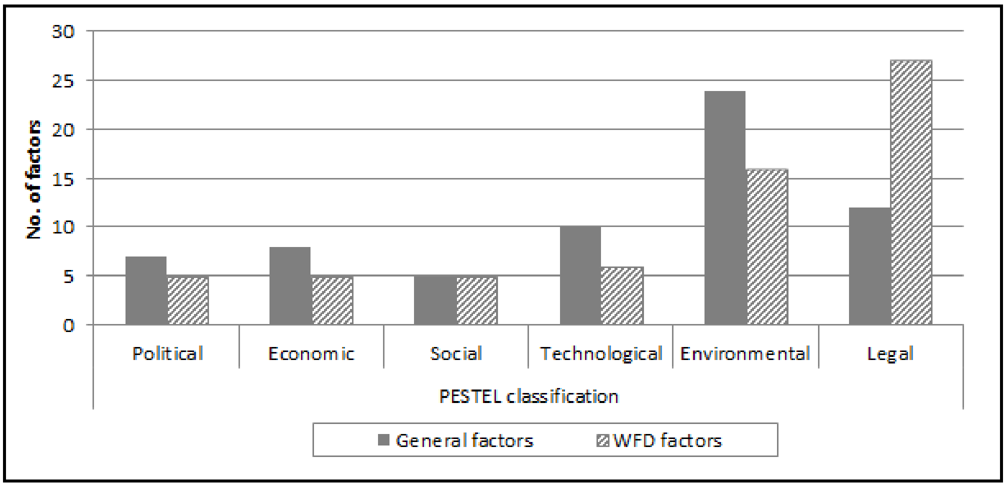

Figure 5.1: PESTEL classification of high impact 'factors'

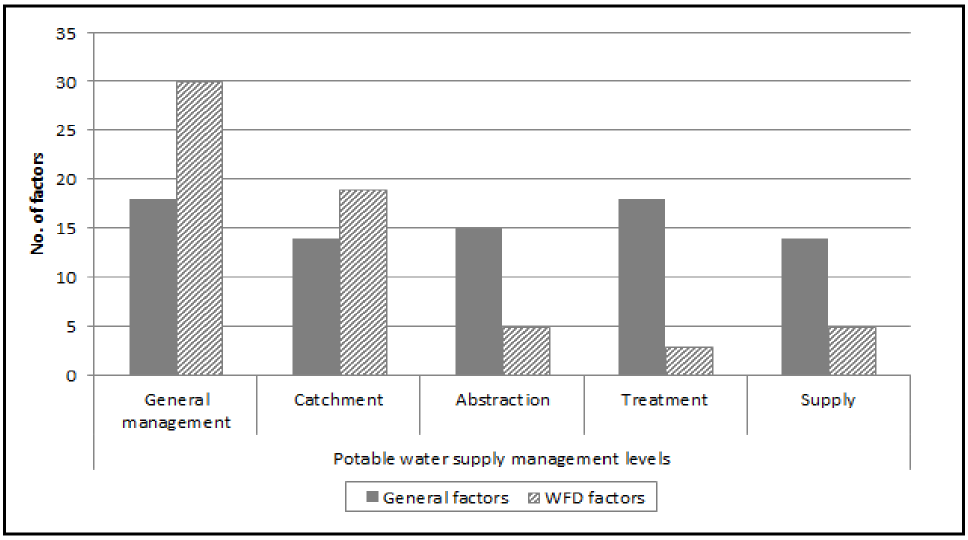

Figure 5.2: High impact ‘factors’ associated with the potable water supply system

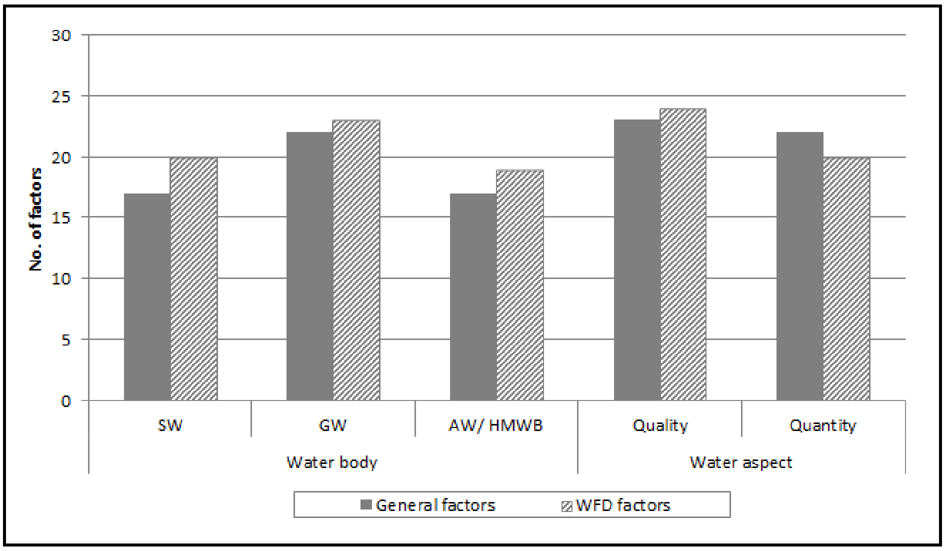

Figure 5.3: No. of high impact 'factors' associated with water characteristics

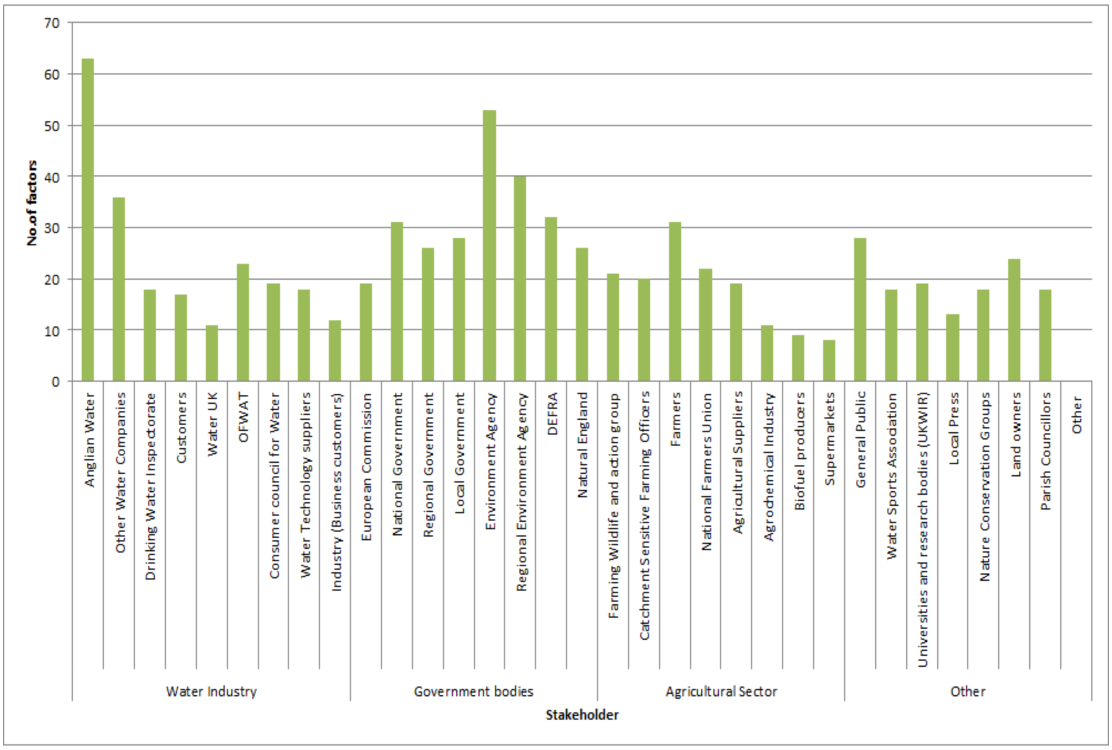

Figure 5.4: Summary of stakeholders associated with identified high impact factors in Step 1.6.

In Figure 5.1 the emphasis of both the ‘general’ and ‘WFD’ factors using the PESTEL framework indicate ‘environmental’ and ‘legal’ as being the most dominant characteristics impacting the management of potable water. Figure 5.2 highlights the focus of ‘general’ factors which address all aspects of the potable water supply chain, with slightly more emphasis at the management of the whole potable water supply system. In contrast however, the ‘WFD’ specific factors were targeted more intensively at the ‘management’ of potable water and at the ‘catchment’ level, with limited direct impact on the ‘abstraction, ‘treatment’ or ‘supply’ level of potable water. Groundwater was identified as being targeted more often by both ‘WFD’ and ‘general’ factors, whilst water quality and quantity were equally targeted by ‘general’ factors, ‘WFD’ specific factors were more focused on water quality (Figure 5.3). The dominant stakeholders affecting the management of potable water, associated with the high impact factors, were recognised in Figure 5.4 as: water companies, the Environmental Agency (national and regional), the government, Defra, farmers, and the general public. Supermarkets, biofuels producers, and water company business customers were identified as being less dominant in relation to the management of potable water supplies. The relative importance of these stakeholders in the management of potable water supplies are further assessed as part of Step 2.6 in Phase 2.

Throughout Steps 1.3-1.8, the classification and characterisation of ‘general’ and ‘WFD’; factors were not necessarily mutually exclusive (i.e. a factor could be classified as ‘political’ and ‘economic’, as well as targeting the ‘catchment level’ and ‘abstraction level’ of the potable water supply chain), and therefore these results are only an indication of the nature of the factors affecting the management of the potable water supply. An understanding of the nature of these factors provides information regarding their impact on and relationships with other ‘factors’ influencing the provision of potable water within subsequent analysis in Steps 1.9 to 1.13 and in Phase 2.

5.3.2 Organisational strategic responses (Step 1.9-1.13)

Through the SWOT analysis (Step 1.9-1.10) conducted on the prioritised factors from Step 1.8, a list of organisational response options (related to resource and/or capability development) were generated (Step 1.11), based on informed judgement by the researcher, evidence from the water company and external data. The organisational responses were classified by the researcher according to the type of ‘resources and capabilities’ required, using categories of ‘human’, ‘intangible’ and ‘tangible’ requirements (Grant, 2005), which are summarised in Figure 5.5.

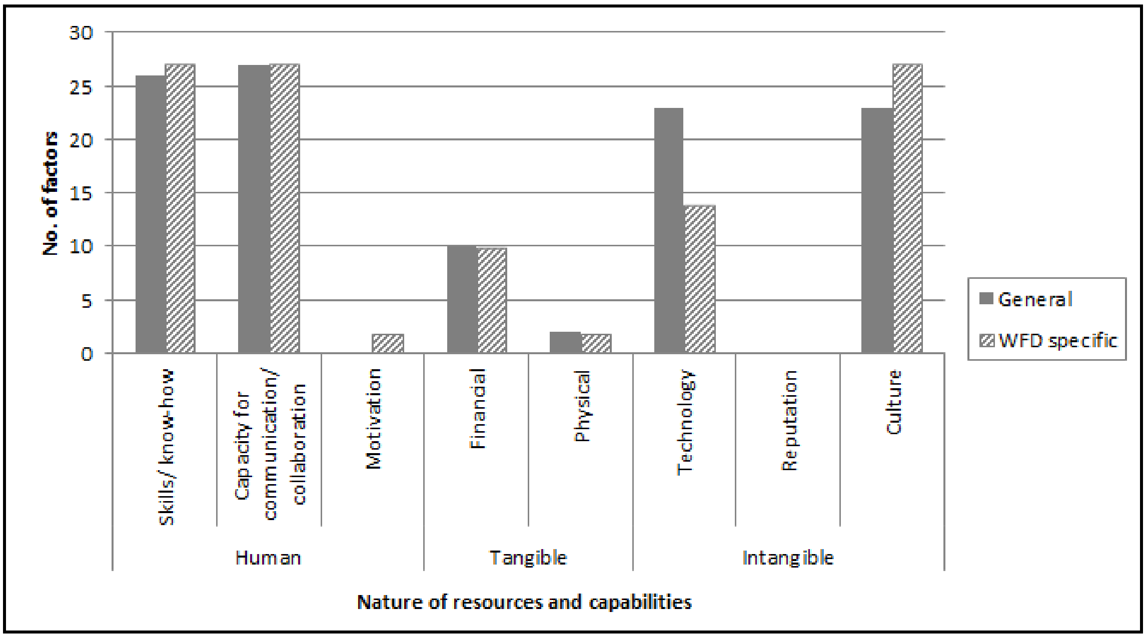

Figure 5.5: Nature of the resources and capabilities to be invested in by the water company.

The nature of the resources and capabilities required indicate an emphasis for responding to the WFD on the development of skills/know-how, communication and collaboration, and cultural changes. This assessment provides an indication of the nature of the organisational responses required to be considered for further investment within the development of potable water management strategies. The organisational response options for each ‘factor’ were amalgamated into a focused set of organisational responses to be considered by the water company for strategic investment (Step 1.12). These are detailed in Table 5.1, and weighted with both the existing strength of the organisation, and strategic importance as required by Step 1.13.

Table 5.1: Resource and capability assessment for organisational responses identified in Step 1.12

Ref	*Resource and capability identified for organisational responses* [d]	*Strategic Importance* [a]	*Relative strength* [a]
		(1-6) [b]	***(1-6)*** [c]
R1	Modelling of future water quality and quantity changes on requirements for water treatment	6	3
R2	Further development of innovative treatment technologies	4	4
R3	Research and investigation in aquifer characteristics and responses to pollution	5	2
R4	Increased monitoring of raw water sources (both parameters and frequency)	5	3
R5	Development of integrated data management (internal and external data) at a catchment level (link into RBMP, legislation requirements, land use, water quality, climate, treatment requirements)	6	1
R6	Organisational understanding of current and future risks to water supplies.	6	3
R7	Preventative investment to reduce risk of pollution of potable water sources.	5	1
R8	Development of the DWSP to include future risks in addition to existing risks	5	2
R9	Trial investigation sites for catchment management intervention by water company to prevent pollution of water sources	6	2
R10	Education and awareness raising of general public, and customers regarding efficient and sustainable water use (incl schools).	6	3
R11	Increased metering installation	5	3
R12	Engagement with stakeholders regarding management of pollution in catchments	6	3
R13	Development of causal analysis techniques to understanding relationships between elements of the management of the potable water supply chain.	6	2
R14	Data sharing with external stakeholders regarding water quality management	5	2
R15	Increased analysis of costs of the provision of water services	5	3
R16	Monitor the effectiveness of legislation implementation/ measures (e.g. safeguard zones, water protection zones, DrWPAs)	6	1

Note:

[a] *Ratings of the strategic importance and relevant strengths are based on the researchers judgement.*

[b] *Scale ranges from 1 to 6 [1 = not important, 2 = not very important, 3 = moderately important, 4 = important, 5 = very important, 6 = extremely important].*

[c] *Scale ranges from 1 to 6 [1 = very low, 2 = low, 3= average, 4= high, 5 = very high, 6 = extremely high].*

[d] *Resources and capabilities are identified from the Phase 1 assessment.*

Based on the level of importance and organisational strength, the following strategic assessment of the responses identifies where further investment might be required (Step 1.13) (Figure 5.6). The responses are indicated by the corresponding reference number (e.g. R1, R2 etc).

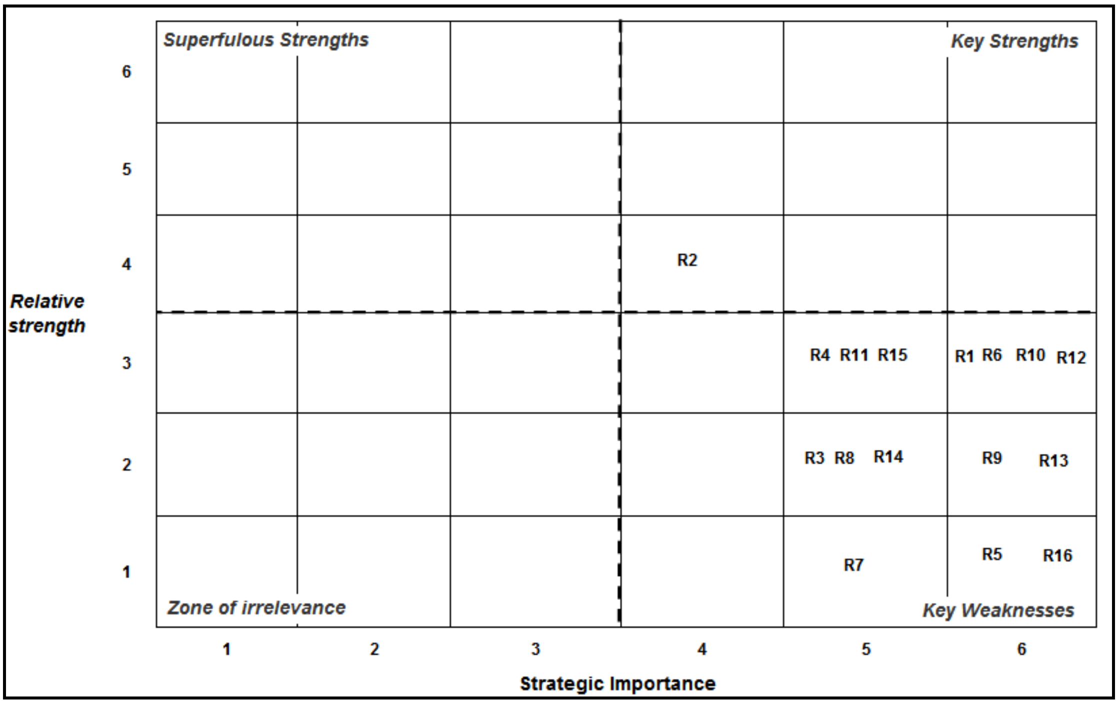

Figure 5.6: Resource and capability strategic assessment.

The ‘key weakness’ quadrant of the matrix identifies the ‘organisational responses’ which require further investment, with integrated data management at a catchment level (R5) and monitoring of the effectiveness of legislation implementation (R16) being considered as of strategically high importance. The development of causal analysis approaches for the management of the risks to the potable water supply chain (R13) and the development of trial catchment management options (R9) are also key strategic responses to be considered. The responses are not mutually exclusive, for example where organisational learning (R6) would be developed as a result of the investment in causal analysis techniques (R13) and development of integrated management of catchment data (R5). The identification of the specific ‘organisational response’ options is further considered in Step 2.17 in the assessment of strategic organisational investment options.

5.3.3 Results from Phase 1

The analysis conducted at the generic level for potable water management has highlighted several points:

Step 1.1-1.8:

- Emphasis is on the management, legal and environmental factors affecting potable water supply
- Water companies, the Environment Agency, and farmers are the key stakeholders.

Step 1.9-1.13:

- Skills and knowledge, communication and collaboration, and cultural changes are required to respond to the WFD requirements.
- Technological resources and capabilities are to be developed to respond to the ‘general’ factors identified.
- Integrated data management at catchment level (R5), monitoring of the effectiveness of legislation implementation (R16,) development of causal analysis approaches for the management of the risks to the potable water supply chain (R13), and the development of trial catchment management options (R9) are high priority development requirements.

This high level analysis of the organisational responses and investment priorities for potable water management is extended to provide a site specific analysis in Phase 2.

5.4 Phase 2: Site specific assessment

5.4.1 Selection and characterisation of site and pressures (Step 2.1 – 2.3)

Factors to be considered for the site and associated pressures in Step 2.1-2.2 were identified from the grey literature, published documents and reports, site specific visits by the researcher, and discussions with water company informants. The number of factors identified and details of the supporting evidence base are listed in Table 5.2. The factors were characterised during Step 2.3 (as previously conducted in Steps 1.3-1.8), and are summarised in Figure 5.7, Figure 5.8, Figure 5.9 and Figure 5.10.

Table 5.2: 'Factors' and 'responses' for consideration in site and pressure specific assessments

Type of factor/ response	Number	Evidence
Factor		
'general' high priority factors	*31*	*As identified in Phase 1*
'WFD' high priority factors	*34*	*As identified in Phase 1*
Site specific	8	Site manuals, technical reports for the site, academic reports for (e.g. soil type, geology).
Pressure specific	21	Industry reports, water company documents, government agency documents.
Total number of factors	**94**	
Response		
Organisational responses	16	(as per Step 1.13)
Additional organisational responses for the specific pressure of nitrate	3	Identified from reference group meetings, and additional activities within the water company (e.g. diffuse pollution forum).
Total number of response	**19**	

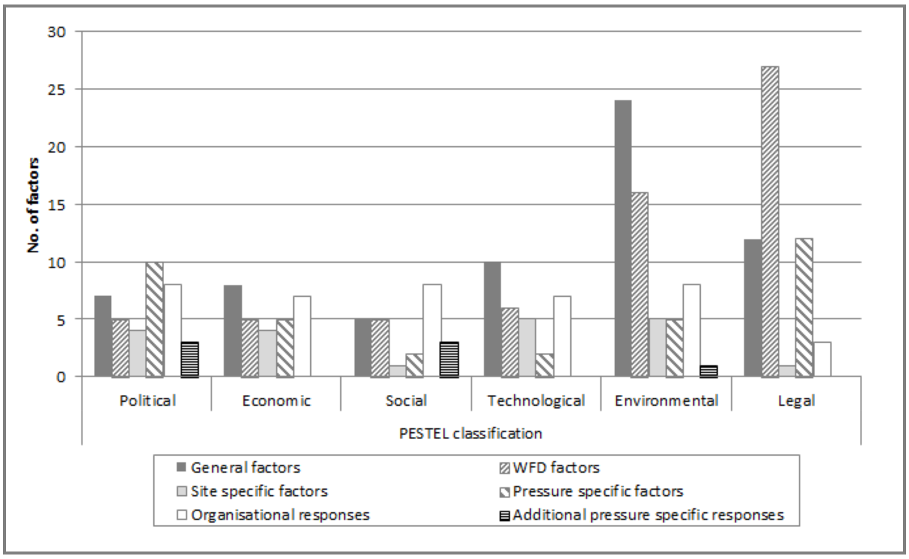

Figure 5.7: PESTEL classification of general, WFD , site specific and pressure specific factors together with organisational and pressure specific responses

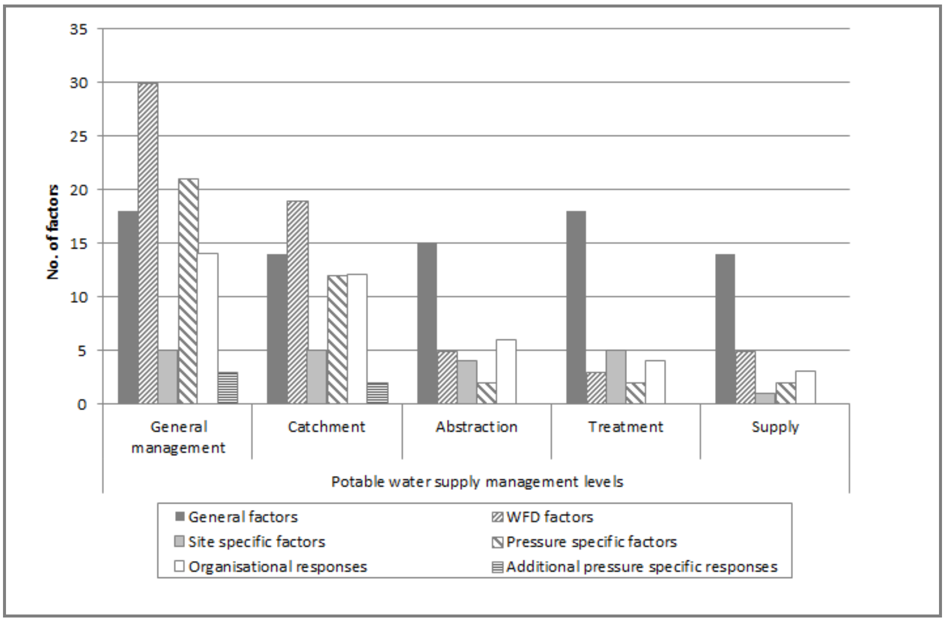

Figure 5.8: Number of 'factors' and 'responses' targeting the management of potable water supply.

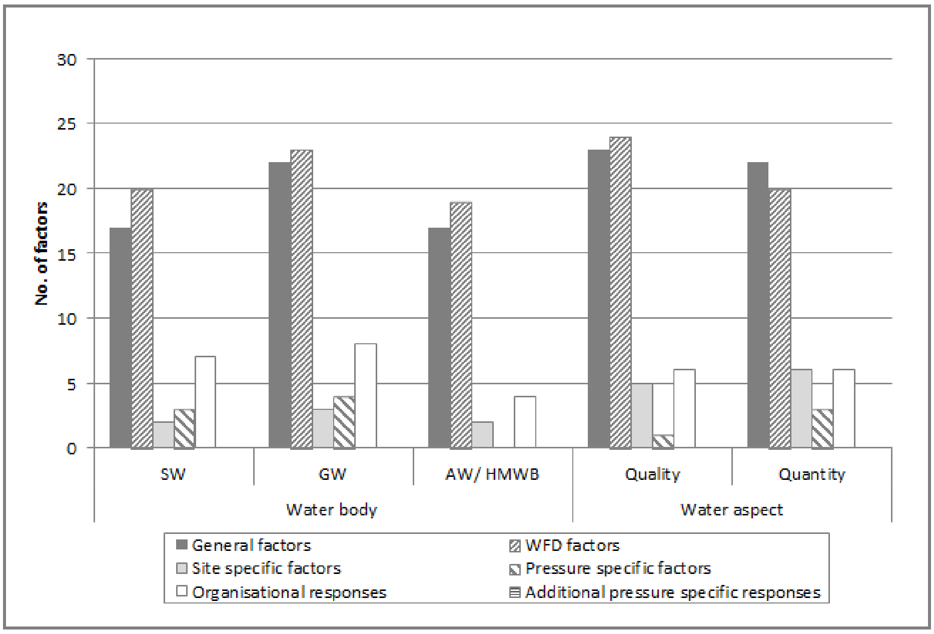

Figure 5.9: Number of 'factors' and 'responses' targeting specific water bodies and water aspects

The factors were not mutually exclusive to specific classifications, and therefore may be represented more than once during their characterisation. In Figure 5.7, the 'pressure specific' factors are principally concerned with political and legal issues, whilst the 'site specific' factors are less focused on legal and social aspects. Organisational responses were characterised as being political, economic, social, technological, and environmental, with less emphasis on legal aspects.

Figure 5.8 indicates that site specific factors are related to each level of the potable water supply chain, whereas pressure specific factors are targeted at the catchment and the general management level. Organisational responses including pressure specific responses, are also targeted at the general management and the catchment level, with less focus on the abstraction, treatment and supply of potable water. Overall more ‘factors’ and ‘organisational responses’ are associated with GW, with marginally more ‘factors’ associated with water quantity (Figure 5.9).

The stakeholders associated with the site specific factors were the same as those identified for the generic factors affecting the management of potable water supply (see Figure 5.4), with the agricultural sector, landowners, and government bodies also identified as dominant stakeholders for the pressure specific factors. The stakeholders and numbers of factors associated with each are illustrated in Figure 5.10.

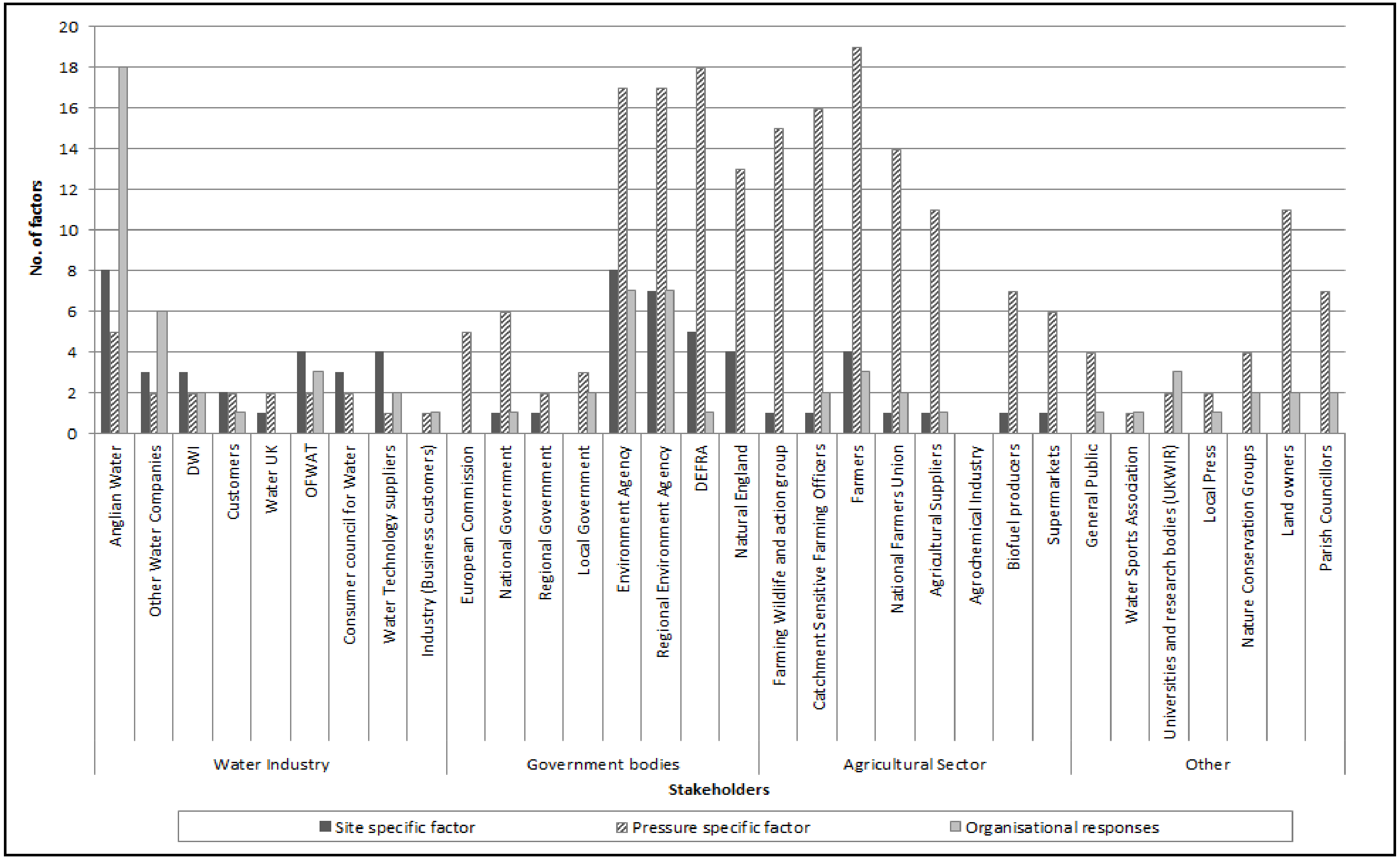

Figure 5.10: Stakeholders associated with site and pressure specific factors, and combined organisational responses.

5.4.2 Causal analysis: factor prioritisation and DPSIR preparation (Step 2.4-2.5)

The DPSIR factors identified were prioritised by the researcher to indicate the likely impact of each factor on the management of the potable water supply chain for the selected site and pressure. From a total of 124 factors, 90 were prioritised as high impact on potable water management and 79 prioritised as high impact on the management of nitrate, although these are not necessarily mutually exclusive. The number of factors classified as D,P,S,I, or R are summarised in Table 5.3 and Table 5.4. The full list of factors to be considered for Barrow and the pressure of nitrate, is provided in Appendix F.

Table 5.3: Summary of factors which have a high effect on potable water management at Barrow.

	General factors	WFD factors	Site specific factors	Pressure specific factors	Organisational response	Additional pressure specific response	Total
Driving Force	1	0	0	3	0	0	4
Pressure	0	0	0	1	0	0	1
State of environment	7	0	4	0	0	0	11
State of water	4	0	0	2	0	0	6
Impact on treatment	5	0	1	0	0	0	6
Impact on supply	2	0	0	0	0	0	2
Impact on management of organisation	1	0	0	1	0	0	2
Response (general and WFD specific)	4	19	0	7	0	0	30
Response (through AW)	8	0	3	0	14	3	28
Total	32	19	8	14	14	3	90

Table 5.4: Summary of factors which have a high effect on the management of nitrate at Barrow.

	General factors	WFD factors	Site specific factors	Pressure specific factors	Organisational response	Additional pressure specific response	Total
Driving Force	1	0	0	4	0	0	5
Pressure	0	0	0	2	0	0	2
State of environment	6	0	3	0	0	0	9
State of water	4	0	0	2	0	0	6
Impact on treatment	5	0	1	0	0	0	6
Impact on supply	1	0	0	0	0	0	1
Impact on management of organisation	1	0	0	0	0	0	1
Response (general and WFD specific)	5	20	0	8	0	0	33
Response (through AW)	4	0	2	0	7	3	16
Total	27	20	6	16	7	3	79

Table 5.3 and Table 5.4 illustrate the range of factors which are identified as being ‘Driving forces’, ‘Pressures’, ‘States’, and ‘Impacts’, with the ‘Responses’ collectively identified to target one of more of the ‘D,P,S,I’ factors to improve potable water management, with regard to nitrate contamination of groundwater. The specific factors which the ‘Responses’ target are presented in a DPSIR grid, which is developed in Step 2.7. A stakeholder analysis of the specific organisational responses identified for the management of the potable water supply chain, and the management of nitrate at Barrow is carried out in Step 2.6 to specifically target stakeholder groups to be engaged with.

5.4.3 Stakeholder analysis (Step 2.6)

The analysis of stakeholders conducted for Barrow is based on the results of the stakeholder analysis conducted with water managers, as well as site specific knowledge from site managers and observations of the location by the researcher. The influential stakeholders to be managed in relation to the groundwater site for Barrow and the management of nitrate pressure are those stakeholders directly related to the high priority factors selected through the DPSIR analysis in Step 2.5. The number of factors which are influenced by each stakeholder are illustrated in Figure 5.11.

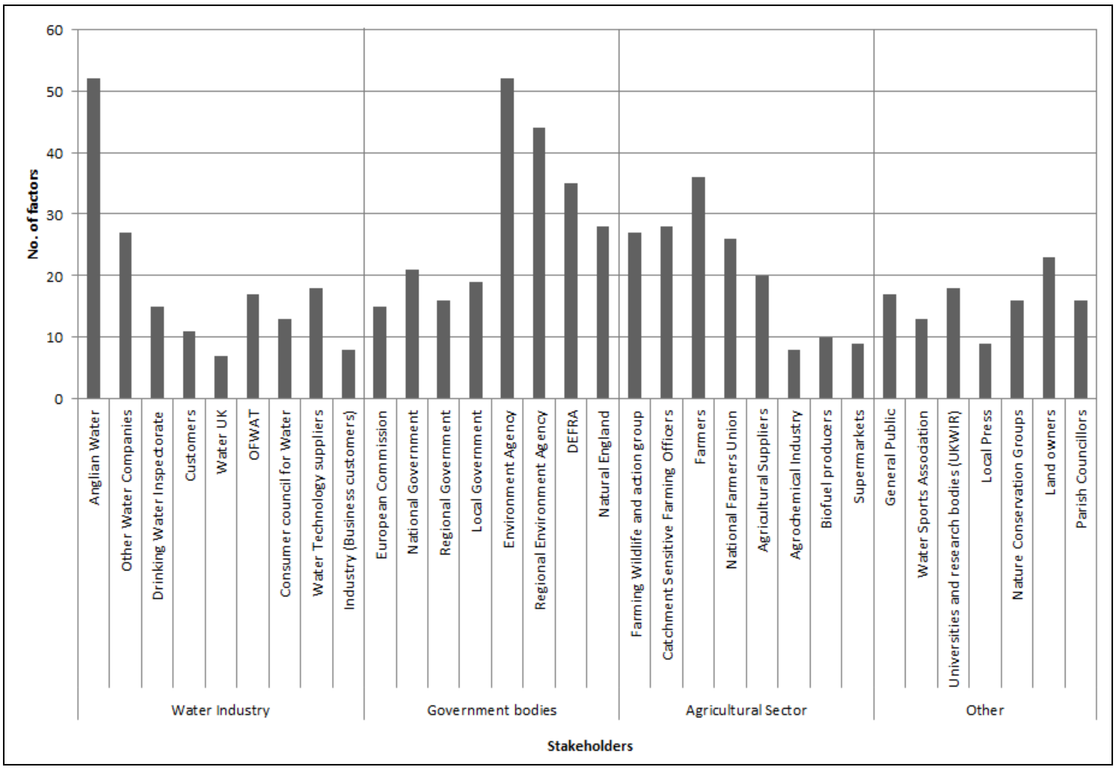

Figure 5.11: Stakeholders associated with the high priority factors from Phase 1 and 2 to be qualitatively analysed in Step 2.6

From this quantitative analysis, the influential stakeholders can be identified as those which are more frequently associated with the high priority factors. Using the understanding of the influential position of the stakeholders from the quantitative analysis, and subjective expert opinion, the level of influence and interest of each of the stakeholders at the Barrow site have been assessed. This assessment allowed the prioritisation of stakeholders to be engaged with to manage the pressure of nitrate at the site. Table 5.5 lists the stakeholders which are assessed, and represented in the stakeholder grid in Figure 5.12.

The ‘key players’ are those stakeholders with which good relationships should be maintained and developed, whilst further development of the relationships with the context setters is required due to their perceived high level of influence. The level of support (positive or negative) of the stakeholders is also identified which allows for an indication as to the nature of the intentions of the stakeholder. Neutral stakeholders (e.g. supermarkets/ biofuel producers) are to be further liaised with to increase their interest and to increase their willingness to support the management of the pressure identified.

Table 5.5: Stakeholder analysis for Barrow

Stakeholders Identified	Level of influence (1-10)	Level of interest (1-10)	Level of support (+)/ (o) /(-)	Nature of stakeholder
Agricultural Suppliers	8	7	o	**Key Player**
Agrochemical Industry	10	10	o	**Key Player**
Anglian Water	6	10	+	**Key Player**
Biofuel producers	7	10	o	**Key Player**
Catchment Sensitive Farming Officers	8	10	+	**Key Player**
Consumer Council for Water	2	2	+	Crowd
Customers	4	5	+	Crowd
DEFRA	10	9	+	**Key Player**
Drinking Water Inspectorate	7	9	+	**Key Player**
Environment Agency	9	10	+	**Key Player**
Environment Agency - Regional	10	8	+	**Key Player**
European Commission	10	8	+	**Key Player**
Farmers	10	6	o	**Key Player**
Farming Wildlife and Action Group	5	8	+	Subjects
General Public	3	5	o	Crowd
Industry (Business customers)	7	1	o	**Context Setters**
Land owners	8	4	o	**Context Setters**
Local Government	7	6	o	**Key Player**
Local Press	8	6	o	**Key Player**
National Farmers Union	8	7	+	**Key Player**
National Government	10	8	+	**Key Player**
Natural England	8	7	+	**Key Player**
Nature Conservation Groups	6	10	+	**Key Player**
OFWAT	10	8	+	**Key Player**
Other Water Companies*	6	10	+	**Key Player**
Parish Councillors	4	1	o	Crowd
Regional Government	10	8	+	**Key Player**
Supermarkets	8	10	o	**Key Player**
Universities and research bodies (UKWIR)	2	7	o	Subjects
Water Sports Association	2	8	+	Subjects
Water technology suppliers**	*2*	*2*	+	Crowd
Water UK	7	5	+	**Context Setters**

Note: (assumed the same value as stakeholder: Anglian Water, ** value designated by researcher.)*
Note: Supportive (+)/ Neutral (o) / Unsupportive (-)

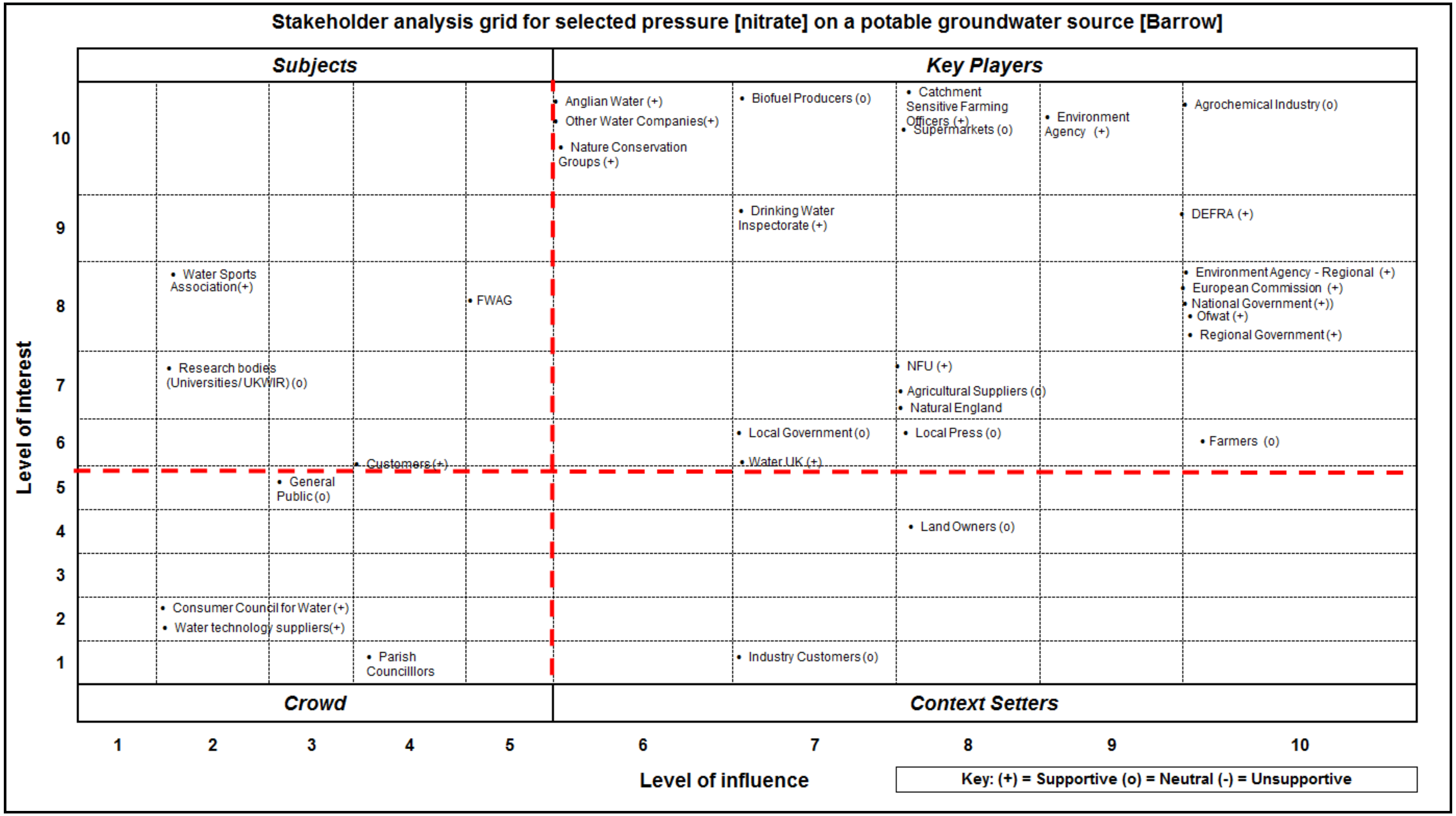

Figure 5.12: Stakeholder analysis grid for Barrow

5.4.4 Causal analysis: DPSIR Grid (Step 2.7)

The factors identified in Step 2.5 are combined for qualitative causal analysis using the 'Driving force, Pressures, Impacts, State and Response' (DSPIR) framework. A DPSIR grid is used to position each of the factors, which are linked using the reference numbers of the factors (Figure 5.13). Using the DPSIR grid, the relationship between the D-P-S-I factors can be identified working down the column, along with each of the responses working down the adjacent columns, and positioned in line with the corresponding D-P-S-I factor which the response targets. Therefore the 'responses' either existing organisational responses, WFD responses or additional organisational responses which target the specific factors in the D-P-S-I chain, which concern the management of nitrate can be identified. This assessment highlights where existing responses are in place to target the D-P-S or I and where additional organisational responses are needed. For example, factor number 54 'Protection of water bodies through safeguard zones' is a WFD response to target factor number 5, 7, 84 and 103, these being 'future water quality', 'water quality trend', 'nitrate concentration in GW', 'water body "at risk" ' respectively. In addition to this WFD response, water company responses of [R1] 'modelling of water quality' and [R2] 'Monitoring of water sources' are also being put in place to target the management of the state of water quality. Other general responses identified in Step 1.13 are also represented in the DPSIR grid (e.g. R14 'Data sharing with stakeholders') to show how all the 'responses' build up to address the impact of nitrate on groundwater, and hence the treatment and supply of potable water. This analysis using the DPSIR grid, ultimately serves the purpose of mapping out how all the different 'responses' target the management of the selected issue of nitrate contamination in groundwater. The causal relationships help to develop understanding by water managers of the variety of factors to be considered in the management of nitrate and subsequently inform the structure of the BNs developed in Steps 2.8 – 2.15.

Ref no.	DPSI factors	Linked to DPSI factor:
	Driving Forces	
33	Type of land use around SPZ	92,93,94
92	Agricultural land use in SPZ1	87,98
93	Agricultural land use in SPZ2	87,98
94	Agricultural land use in SPZ3	87,98
	Pressures	
87	Farming practices	5,6,7,84
98	Nitrate application to land.	5,6,7,84

Ref no.	Reponses (existing and identified WFD responses) - Not Anglian Water	Linked to DPSI factor:	Ref no.	Anglian Water Response Options	Linked to DPSI factor:
27	Political steer from government	ALL			
69 (70)	RBMP production and review (every 6yrs)	ALL			
13	Environmental legislation compliance	87,98	R7	Investment to target the cause of potable water source pollution	87,98
38	Financial penalties for WFD none compliance	87,98	R16	Monitor the effectiveness of implementation of legislation	13,38,45,57,63,64,65,66,67,74,88,89,90,91,95,99,100
45	WFD objective	87,98	R1A	Liaise directly with farmers to educate and raise awareness	87,98
57 (58, 68)	Programmes of measures (basic and supplementary)	87,98	R2A	Workshop with local stakeholders regarding GW pollution	87,98
63	Basic measures to prevent or control point sources of pollution	87,98			
64	Basic measures to prevent or control diffuse sources of pollution	87,98			
65	Basic measures to prohibit direct discharges into groundwater	87,98			
66	Basic measures to eliminate pollution of surface water	87,98			
67	Basic measures to prevent loss of pollutants	87,98			
74	Prevent and control groundwater pollution	87,98			
88	NVZ enforcement effectiveness	87,98			
89	Groundwater daughter Directive effectiveness	87,98			
90	Entry level schemes	87,98			
91	Higher level schemes	87,98			
95	Catchment Sensitive Farming Area	87,98			
99	NVZ compliance	87,98			
100	Financial penalties for non-compliance with NVZ	87,98			

Ref no.	Anglian Water Response Options	Linked to DPSI factor:
R5	Integrated data management development	ALL
R6	Develop organisational understanding	ALL
R8	DWSP development	ALL
R9	Catchment Management trials	ALL
R10	Education and awareness of stakeholders	ALL
R12	development of relationships and engagement with stakeholders	ALL
R13	Use of causal analysis techniques to understand integrated management of potable water	ALL
R14 &R3A	Data sharing with stakeholders	ALL

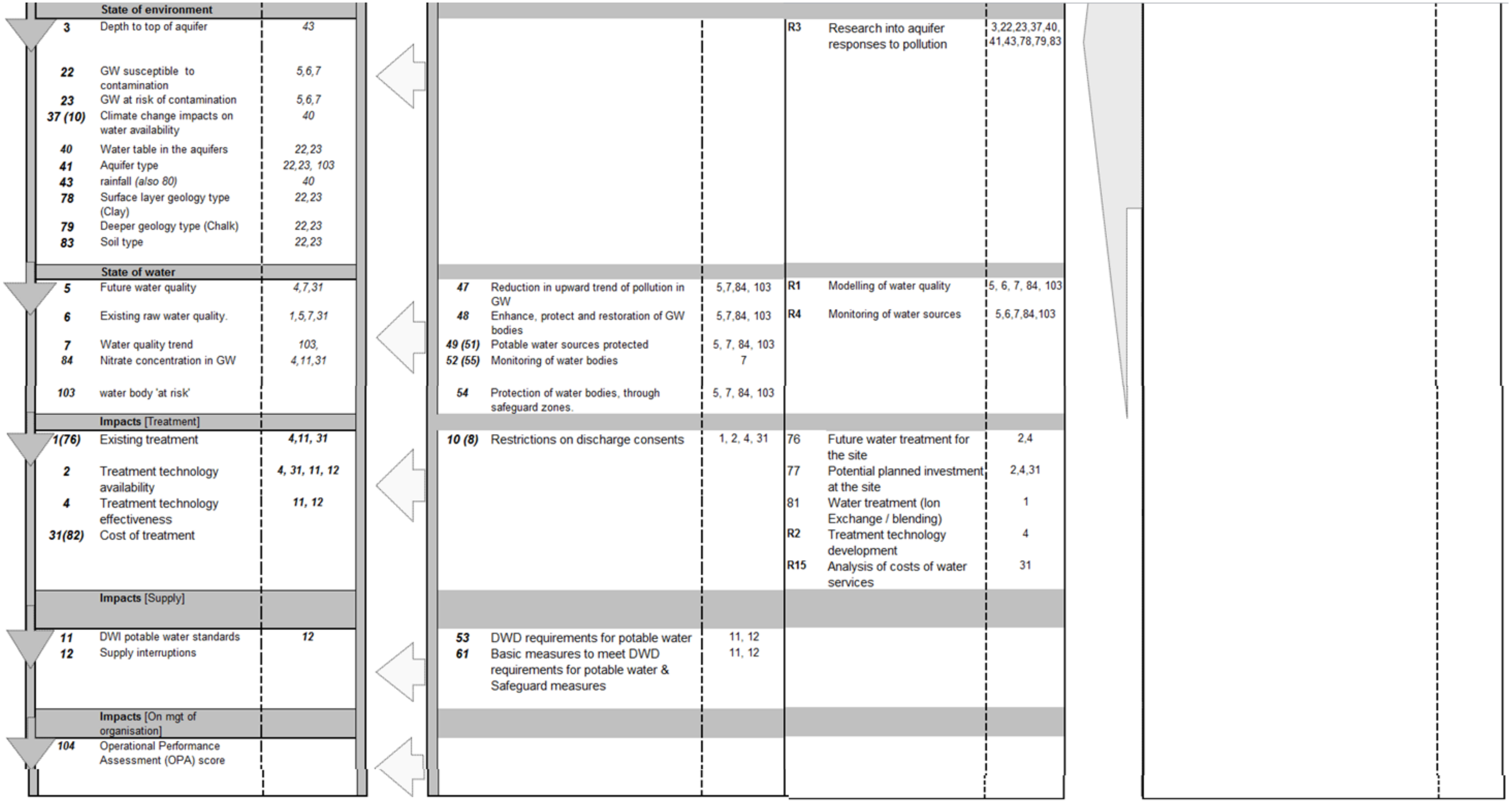

Figure 5.13: DPSIR causal analysis grid

5.4.5 Bayesian Network Development (Step 2.8-2.15)

The factors identified from the DPSIR prioritised list in Step 2.5, are used as the basis to determine the system boundary conditions used for the development of the Bayesian network. The factors selected to be incorporated within the BN are illustrated in the conceptual system in Figure 5.14.

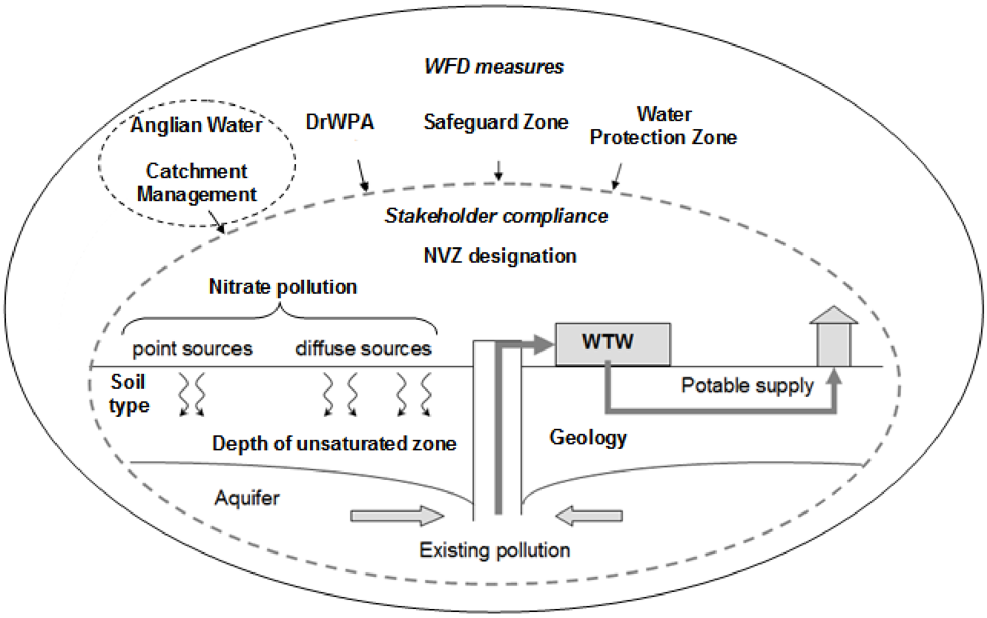

Figure 5.14: Conceptual system for the identification of the boundaries and variables for the development of the Bayesian network for Barrow.

The BN constructed for Barrow (using Hugin A/S Expert software) consists of 94 variables (nodes), which represent the changes in nitrate concentration in raw water and management of nitrate and potable water over time. Hence the BN is classified as a dynamic BN, through the incorporation of time steps related to both the AMP five year planning period, and the RBMP six year planning period. The variables and the associated probability distributions used in the BN for Barrow are presented within this section.

The development of the structure and probability distributions for the BN for Barrow has been conducted by the researcher informed by discussions with key informants, primary information supplied by the water company and other external sources, and additionally supported by academic literature. The sources of the data for each of the component parts of the BN are detailed within the corresponding sections within this chapter. Where data were unavailable to inform the resting states of the variables, and the CPTs, probability values were developed, based on qualitative statements, and using the scale presented in Figure 5.15, adapted from Kjaerulff and Madsen, (2008).

Certain	Very Likely	Likely	Probable	Fifty-fifty	Not probable	Unlikely	Very unlikely	Impossible
1	0.99	0.9	0.8	0.5	0.2	0.1	0.01	0

Figure 5.15: Mapping of statements of probability to probabilities (adapted from Kjaerulff and Madsen, 2008:165)

In Table 5.6, the variables included in the BN are presented. The reference numbers refer to the original variable identified from the main workbook. Some "factors" were combined with or formed the basis of additional variables within the BN, which were determined by the researcher during the development of the BN. For example the variable 'BN 16' termed "DrWPA in RBMP 1" is a combination of the original WFD factors 48, 49 and 51, 'enhance, protect and restore GW bodies' (Article 4 [1] [b] [ii]), 'potable water resources protected' (Article 4[1][i]), 'protected areas identified' (Article 6).

Table 5.6: Factors selected for inclusion as "variables" within the BN (Step 2.8)

BN ref number	*Original reference*	Abbreviated name for variable in Bayesian network	State of variable	***Data Reliability**	***Data Accuracy**
BN 01	*99*	Stakeholder NVZ compliance	compliant, non-compliant	A	3
BN 02	*88*	Existing NVZ designation	designated, not designated	C	4
BN 03	*88*	Effectiveness of NVZ	effective, not effective, no measures	C	4
BN 04	*98*	Uncontrolled diffuse sources in SPZ	yes, no	C	5
BN 05	*98*	Uncontrolled point sources in SPZ	yes, no	C	5
BN 06	*23*	Existing risk of GW pollution	high, low	C	5
BN 07	***R9***	AW Catchment Management in AMP 5	implemented, not implemented	D	X
BN 08	*99*	Stakeholder NVZ compliance RBMP 1	compliant, non-compliant	A	3
BN 09	*99*	Stakeholder WFD measures compliance in RBMP 1	compliant, non-compliant	A	3
BN 10	*88*	NVZ designation RBMP 1	designated, not designated	C	4
BN 11	*88*	Effectiveness of NVZ RBMP 1	effective, not effective, no NVZ	C	4
BN 12	*98*	Uncontrolled point sources in SPZ RBMP 1	yes, no	C	5
BN 13	*23*	Risk of GW pollution 2010-15	high, low	C	5
BN 14	*98*	Uncontrolled diffuse sources in SPZ RBMP 1	yes, no	C	5
BN 15	*R16*	Effectiveness of protection measures RBMP 1	effective, not effective, no measure	D	X
BN 16	*48*	DrWPA in RBMP 1	designated, not designated	A	3
BN 16	*49*	DrWPA in RBMP 1	designated, not designated	A	2
BN 16	*51*	DrWPA in RBMP 1	designated, not designated	A	3
BN 17	*102*	Safeguard zone RBMP 1	designated, not designated	A	1
BN 18	*101*	WPZ in RBMP 1	yes, no	A	1
BN 19	*23*	GW at risk of failure of WFD objectives by 2015.	high, low	C	5
BN 19	*103*	GW at risk of failure of WFD objectives by 2015.	high, low	A	1
BN 20	*42*	Soil permeability	high permeability, low permeability	A	2
BN 20	*83*	Soil permeability	high permeability, low permeability	A	3
BN 21	*22*	Geology type	chalk, other	C	5
BN 22	*3*	Depth of unsaturated zone	shallow, deep	A	1
BN 23	*22*	GW vulnerability to contamination	yes, no	C	5
BN 24	*47*	Current trend of GW quality	upward, stable, decreasing	A	3
BN 25	*6*	Current raw water quality	<45 mg/l, > 45 mg/l	A	2
BN 26	*1*	Blending used	yes, no	A	1
BN 27	-	Alternative sources	yes, no	A	1
BN 28	*6*	Nitrate concentration of alternative source	< 45 mg/l, > 45 mg/l	A	2

BN ref number	*Original reference*	Abbreviated name for variable in Bayesian network	State of variable	**Data Reliability*	**Data Accuracy*
BN 28	*11*	Nitrate concentration of alternative source	< 45 mg/l, > 45 mg/l	A	1
BN 29	*11*	Blended water quality	< 45 mg/l, > 45 mg/l	A	1
BN 30	*81*	Ion exchange used	yes, no	A	1
BN 31	*11*	Processed water quality in AMP 5	< 45 mg/l, > 45 mg/l	A	1
BN 32	*11*	Potable water standards	< 45 mg/l, > 45 mg/l	A	1
BN 33	*7*	Trend in GW quality in 2015	upward, stable, decreasing	A	2
BN 34	*6*	GW quality in 2015	upward, stable, decreasing	A	2
BN 34	*23*	GW quality in 2015	upward, stable, decreasing	C	5
**Note: Definitions of data accuracy and reliability are provided in Table 4.8 and Table 4.9 within Chapter 4.*					

The main assumptions within this representation of the problem domain for Barrow include:

1. Management of nitrate pollution is determined by the designation as a protected area (either Nitrate Vulnerable Zone or through WFD protection measures), in combination with the compliance status of the stakeholders responsible for the implementation of the measures.
2. Vulnerability of the groundwater to pollution is determined by a wide range of physical characteristics although only three main factors are presented for simplicity (soil permeability, geology, depth of unsaturated zone).
3. The risk presented by point and diffuse nitrate sources on groundwater quality is assumed to have a cumulative impact, where initial implications of changes in the management of nitrate pollution are assumed to have an effect within 5 years. This is based on the relatively shallow groundwater source for Barrow, and the permeability of the chalk geology. The exact timescale for movement of pollution through the geology is unknown for Barrow. (The temporal period is reflected in the structure of the Bayesian network).
4. The quantity of water required for supply is not considered, therefore the blending option for the management of potable water in this instance is to improve the overall water quality below the 45 mg/l internal standard. Hence the quality of the water is used as the trigger for potential investment options.
5. The availability of alterative water sources (e.g. from Goxhill, Barton and Thornton) is assumed to be assessed separately in each AMP period. The

availability would be subject to the catchment conditions around each of the alternative groundwater sources, which require separate consideration and are outside the scope of this BN.

6. The blend source available is considered to a combined source from adjacent boreholes (Thornton, Goxhill and Barton). These sources are located within 3 miles of the Barrow source, although exhibit different geological profiles, and different management practices within their source protection zones. The variability of the water quality from these sources is outside the scope for the Barrow case study, although it is acknowledged they impact on the WTW at Barrow.

An overview of the final Bayesian network developed for Barrow is presented in Figure 5.16. It incorporates the time slices related to both the implementation of the subsequent RBMPs and the management of potable water through the successive AMP periods. In total there are 94 variables in the network, although the CPTs developed and presented in this section are for the 34 baseline variables which represent the current conditions. These variables are incorporated within the components: ‘management of the catchment’ (19 variables within “Before RBMP” and “RBMP 1[2009-2015]”), the starting ‘physical conditions’ for the site (four variables), and the ‘management of potable water’ specifically the initial AMP 4 (2005-2010) period (nine variables) Figure 5.16.

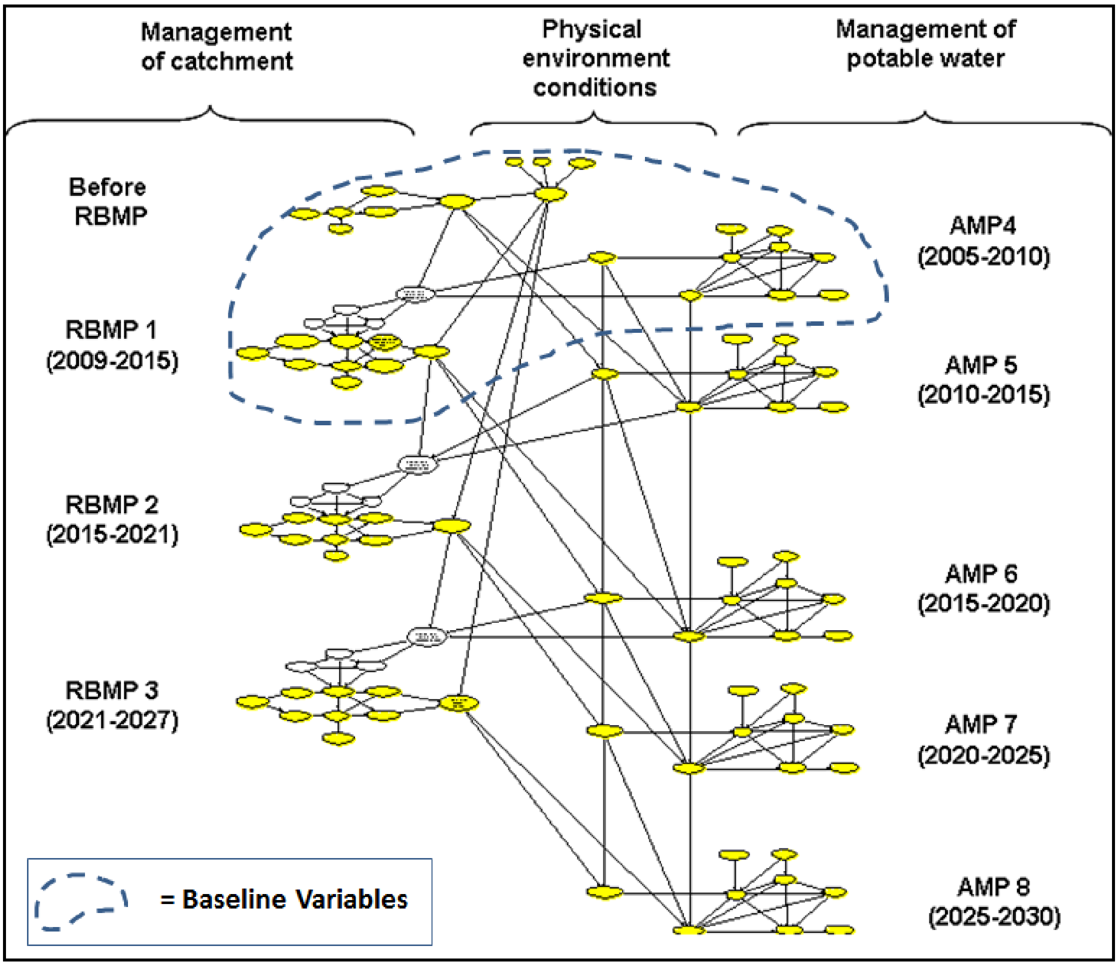

Figure 5.16: Overview of the Bayesian network structure for the Barrow case study

The three main sections of the Bayesian network related to the 'management of the catchment', the 'physical environment', and the 'management of potable water' are introduced and explained in the following sections. Each of the 34 baseline variables (also referred to as nodes), their states and the associated CPTs are explained sequentially within this chapter, and form the basis of subsequent CPTs used for the remaining 60 variables within the network. The variables are initially introduced and are subsequently referred to via the 'BN XX' reference as listed in Table 5.6.

5.4.6 Barrow BN component 1: Management of the catchment

In this section the variables, their states, and prior probabilities are explained as well as the associated CPTs for the BN component, 'management of the catchment'. The first part of this component relates to catchment management prior to WFD implementation (Figure 5.17) which is followed by the second part related to the implementation of the first RBMP (Figure 5.18).

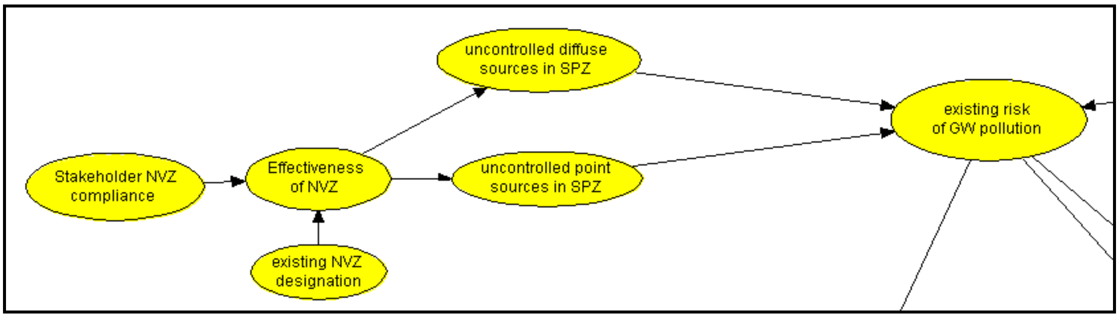

Figure 5.17: Bayesian network variables for the catchment management component prior to WFD implementation

The parent node 'stakeholder NVZ compliance' (BN 01) has states of 'compliant' or 'non-compliant', and parent node 'existing NVZ designation'(BN 02) has states of 'designated or not designated'. The prior probabilities for BN 01 are 0.8 for 'non-compliant' and 0.2 for 'compliance', and for BN 02 are 0 for 'not designated' and 1 for 'designated'. These prior probabilities have been informed from liaison with the Environment Agency regarding the level of compliance with NVZ for the Barrow region, and the onsite observations of manure heaps within the SPZ together with livestock grazing. The probability associated with the states of these parent nodes directly influence the states of the child node 'effectiveness of NVZ' (BN 03) which are 'effective', 'not effective' and 'no NVZ'. The conditional probabilities associated with the states of the parent nodes (BN 01, BN 02) and those of the child node (BN 03) are represented in Table 5.7. Where 'no NVZ' is designated the effectiveness is not able to be considered, therefore a probability of 1 is allocated. Although this could be considered to be equivalent to not effective, it is treated separately due to the relationship to the designation status of NVZ, and therefore represents the conditions required for states within a BN to be mutually exclusive and exhaustive. Where the

NVZ is ‘designated’ and the stakeholders are ‘compliant’, the NVZ legislation is believed by the researcher to have a probability of 0.9 for being effective. Conversely where ‘non-compliance’ is observed, a probability of 0.1 is believed to be appropriate. There is limited data available to inform these CPTs, although it has been assumed that where NVZ legislation is effectively implemented the conditions required for the containment and management of nitrate pollution is conducted in a controlled manner.

Table 5.7: CPT for ‘Effectiveness of NVZ’ (BN 03)

Existing NVZ designation	*Designated*		*Not designated*	
Stakeholder NVZ compliance	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*
Effective	0.9	0.1	0	0
Not effective	0.1	0.9	0	0
No NVZ	0	0	1	1

Two variables concerned with the management of nitrate in the catchment which are informed by BN 03 are ‘uncontrolled diffuse sources in SPZ’ (source protection zone) (BN 04), and ‘uncontrolled point sources in SPZ’ (BN 05). BN 04 and BN 05 have Boolean states of ‘yes’ or ‘no’ and are represented together with the conditional probabilities in Table 5.8 and Table 5.9. Where the NVZ legislation (BN 03) is considered to be ‘effective’, the probability distribution across states ‘yes’ and ‘no’ of BN 04 and BN 05 are believed to be 0.1 and 0.9 respectively. Conversely where BN 03 is ‘not effective’ the probability distribution is reversed, becoming 0.9 for ‘yes’ and 0.1 for ‘no’, to indicate point or diffuse sources are more likely to be uncontrolled. Where ‘no measures’ for BN 03 are identified, this indicates the area has not been designated as a NVZ. There is no guarantee of the absence of diffuse sources, and therefore the probability of 0.2 (not probable) has been assumed for BN 04 and BN 05 for state ‘yes’ indicating the presence of pollution and a probability of 0.8 (probable) for state ‘no’ indicating the absence of pollution. This is based on the assumed low risk of pollution present due to no designation of measures to control it, although in the future this may change, and hence these probabilities may require updating.

Table 5.8: CPT for ‘Uncontrolled diffuse sources in SPZ’ (BN 04)

Effectiveness of NVZ	*Effective*	*Not effective*	*No measures*
Yes	0.1	0.9	0.2
No	0.9	0.1	0.8

Table 5.9: CPT for 'Uncontrolled point sources in SPZ' (BN 05)

Effectiveness of NVZ	*Effective*	*Not effective*	*No measures*
Yes	0.1	0.9	0.2
No	0.9	0.1	0.8

The resulting risk of GW pollution within the catchment around Barrow is represented by variable 'existing risk of GW pollution' (BN 06) from nitrate, which has Boolean states of 'high' or 'low'. BN 06 is informed by both BN 04 and BN 05 as well as a further variable 'GW vulnerability to nitrate contamination' (BN 23) from the 'physical environment component' of the BN (see Section 5.4.7). The CPT representing the relationships between these variables and the states of BN 06 are represented in Table 5.10. Where the GW is vulnerable to nitrate contamination (i.e.BN 23 is in state 'yes'), and diffuse and point sources of nitrate pollution are present (i.e. BN 04 and BN 05 both have state 'yes'), a probability of 0.99 is assumed for BN 06 having a 'high' risk of GW nitrate pollution. Where either diffuse or point sources of nitrate are present (i.e. one of BN 04 or BN 05 has the state of 'yes') and the GW is considered to be vulnerable to nitrate pollution (i.e. BN 23 has state 'yes'), a probability of 0.8 is assumed to indicate a 'high' risk of the GW being polluted, with a corresponding 0.2 for 'low' risk of GW pollution. Conversely where no nitrate pollution is present within a vulnerable GW body (i.e. BN 04,05 and 23 are in state 'no') or where the GW is not vulnerable (i.e. BN 23 is in state 'no'), even with nitrate pollution present, a probability of 0.1 (unlikely) is assumed for the state of 'high' risk and 0.9 (likely) for 'low' risk of GW pollution.

Table 5.10: CPT for 'Existing risk of GW pollution' (BN 06)

<table>
<tr><td>Uncontrolled diffuse sources of nitrate in SPZ</td><td colspan="4">Yes</td><td colspan="4">No</td></tr>
<tr><td>Uncontrolled point sources of nitrate in SPZ</td><td colspan="2">Yes</td><td colspan="2">No</td><td colspan="2">Yes</td><td colspan="2">No</td></tr>
<tr><td>GW vulnerability to nitrate contamination</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td><td>Yes</td><td>No</td></tr>
<tr><td>High</td><td>0.99</td><td>0.1</td><td>0.8</td><td>0.1</td><td>0.8</td><td>0.1</td><td>0.1</td><td>0.01</td></tr>
<tr><td>Low</td><td>0.01</td><td>0.9</td><td>0.2</td><td>0.9</td><td>0.2</td><td>0.9</td><td>0.9</td><td>0.99</td></tr>
</table>

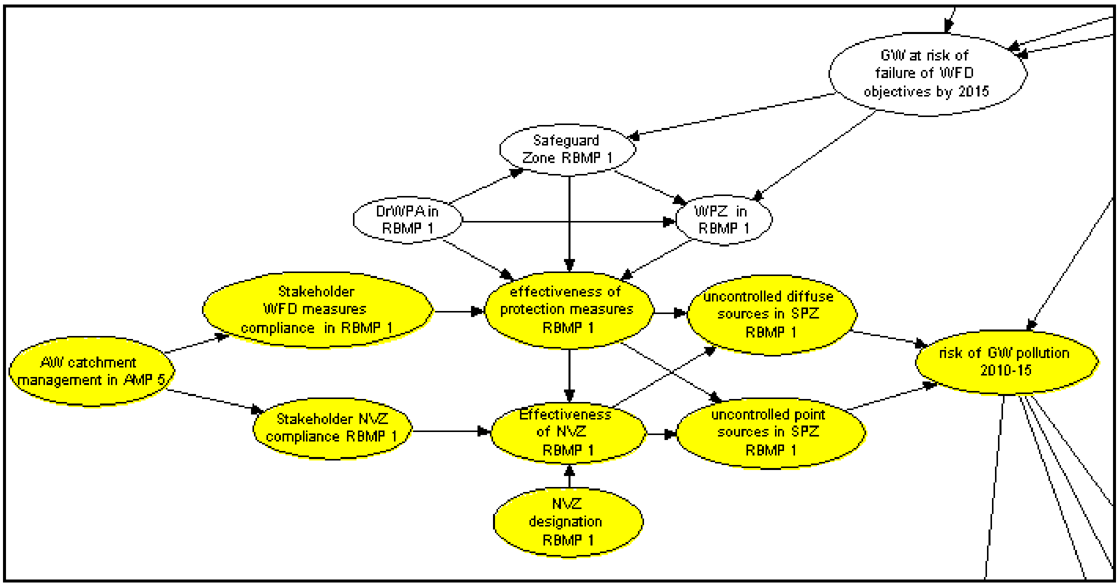

Figure 5.18: Bayesian network variables associated with the management of the catchment in the first RBMP

The part of the BN represented in Figure 5.18 depicts the variables associated with the implementation of the first RBMP (2009-2015). The parent variable of ‘AW catchment management in AMP5’ (BN 07) has been introduced as an additional variable through the analysis of resources and capabilities conducted in Hybrid-DSP Phase 1. This has been verified as a proposed investment option for Barrow through the development of the Anglian Water catchment management strategy for AMP 6, where an investigation into the management of the risk of nitrate pollution is considered for the Barrow catchment. The states of ‘implemented’ and ‘not implemented’ are used with the prior probabilities of 0.5 respectively, due to no current implementation of catchment management. The subsequent influence of variable BN 07 on variables ‘stakeholder NVZ compliance RBMP1’ (BN 08) and ‘Stakeholder WFD measures compliance in RBMP 1’ (BN 09) are represented through the respective conditional probabilities in Table 5.11 and Table 5.12.

Table 5.11: CPT for ‘Stakeholder NVZ compliance RBMP 1’ (BN 08)

Anglian Water Catchment Management in AMP 5	*Implemented*	*Not implemented*
Compliant	0.6	0.5
Non-compliant	0.4	0.5

Table 5.12: CPT for 'Stakeholder WFD measures compliance in RBMP 1' (BN 09)

Anglian Water Catchment Management in AMP 5	*Implemented*	*Not implemented*
Compliant	0.6	0.5
Non-compliant	0.4	0.5

The influence of the 'catchment management' intervention (BN 07) by Anglian Water is considered to have a marginal increase in the level of stakeholder compliance with both the NVZ and WFD legislative measures (BN 08 and BN 09), hence probability of 0.6 for 'compliant' and 0.4 for 'non-compliant'. This is based on evidence from other case studies (e.g. Wessex Water), where stakeholder engagement and liaison with stakeholders within a SPZ regarding the management of nitrate on land has resulted in improved land management practices regarding the management of sources of pollution. This was identified through personnel communication with key informants at Wessex Water (ID47, ID57, ID72) and a site visit to observe catchment management practices. The probabilities are only marginally increased, due to the acknowledgement of the need to build location specific relationships with the stakeholders. Limited relationships have been developed with stakeholders around the Barrow catchment, and therefore would require further development over time to allow for an increased probability of influencing the level of compliance of the stakeholders.

The Drinking Water Protection Area (DrWPA) parent variable 'DrWPA in RBMP 1' (BN 16) is considered to have states of 'designated' or 'not designated' within the SPZ. In the Barrow catchment the SPZ has been also been designated as a DrWPA as stated within the Humber RBMP (EA, 2009b), and therefore the state of 'designated' is determined. In subsequent RBMP cycles, a prior probability of 0.9 (likely) and 0.1 (unlikely) is assumed, due to the potential for continuation of the DrWPA designation. In addition to the DrWPA, the legislative designations of a safeguard zone, as well as a water protection zone (WPZ) is also included in the BN. These are represented as variables 'safeguard zone RBMP 1' (BN 17) and 'WPZ in RBMP a' (BN 18). The CPT for the designation of additional legislative GW protection of a 'safeguard zone' (BN 17) is presented in Table 5.13. The designation of a safeguard zone has been determined within the Humber RBMP (EA, 2009b), and therefore the probability of 1 for the condition of high risk of failure and prior DrWPA designation is determined. In subsequent RBMP cycles the prior probabilities are considered to be 0.9 and 0.1 for safeguard zone 'designated' and 'not designated' respectfully. This is based on an assumption of the continuation of the implementation of WFD protection measures.

Table 5.13: CPT for 'Safeguard Zone designation in RBMP 1' (BN 17)

GW at risk of failure of WFD objectives by 2015	*High*		*Low*	
DrWPA in RBMP 1	*Designated*	*Not designated*	*Designated*	*Not designated*
Designated	1	0.5	0.5	0.01
Not designated	0	0.5	0.5	0.99

The variable 'WPZ in RBMP 1' (BN 18) refers to the designation of the Barrow catchment as a Water Protection Zone (WPZ) during the first RBMP cycle. The CPT for 'WPZ in RBMP 1' (BN 18) is presented in Table 5.14 and is informed by the researcher. The probability of the designation of the area being a WPZ is dependent on the risk of failure of the WFD objectives (BN 19), and the prior designation of DrWPA (BN 16) and safeguard zones (BN 17). In the initial RBMP cycle the Barrow catchment was not designated a WPZ, and therefore has the state of 'not designated'. This is due to the newness of the measure, which is being trialled on selected sites (EA, 2009). This is assumed to change over subsequent RBMPs, where the designation of WPZs will become more likely when there is a risk of the failure of WFD objectives. This has been reflected in the CPT for 'WPZ designation in RBMP 2 and 3', where designation is considered to be likely with a probability of 0.9 when a high risk of failure of the WFD objectives is evident even with the existing designation of DrWPA and Safeguard Zones within the catchment.

The variable 'effectiveness of protection measures RBMP 1' (BN 15) has states of 'effective', 'not effective' and 'no measures', and is influenced by variables BN 09, BN 16, BN 17, BN 18. The relationship of these variables to the states of BN 15 are represented in Table 5.15. The CPT has been based on the assumption that where stakeholders are compliant, the measures are considered to be effective. An increase in the number of measures consisting of DrWPA, Safeguard Zone and Water Protection Zone are assumed to increase the probability of the stakeholder being compliant.

Table 5.14: CPT for ‘WPZ designation in RBMP 1’ (BN 18)

GW at risk of failure of WFD objectives by 2015	*High*				*Low*			
DrWPA in RBMP 1	*Designated*		*Not Designated*		*Designated*		*Not Designated*	
Safeguard zone RBMP 1	*Designated*	*Not designated*	*Designated*	*Not designated*	*Designated*	*Not designated*	*Designated*	*Not designated*
Yes	0	0.5	0.5	0.5	0.1	0.1	0.1	0
No	1	0.5	0.5	0.5	0.9	0.9	0.9	1

Table 5.15: CPT for the ‘effectiveness of protection measures RBMP 1’ (BN 15)

Stakeholder WFD compliance in RBMP 1	*compliant*								*Non-compliant*							
DrWPA in RBMP 1	*designated*				*Not designated*				*designated*				*Not designated*			
Safeguard zone designated in RBMP 1	*Designated*		*Not designated*		*Designated*		*Not designated*		*Designated*		*Not designated*		*Designated*		*Not designated*	
WPZ in RBMP 1	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Effective	0.99	0.85	0.8	0.8	0	0	0	0	0.2	0.15	0.1	0.1	0	0	0	0
Not effective	0.01	0.15	0.2	0.2	0	0	0	0	0.8	0.85	0.9	0.9	0	0	0	0
No measures	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1

Table 5.16: CPT for ‘effectiveness of NVZ RBMP 1’ (BN 11)

Effectiveness of nitrate protection measures RBMP 1	*effective*				*Not effective*				*No measures*			
NVZ designation RBMP 1	*Designated*		*Not designated*		*Designated*		*Not designated*		*Designated*		*Not designated*	
Stakeholder NVZ compliance RBMP 1	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*	*Compliant*	*Non-compliant*
Effective	0.99	0.01	0	0	0.9	0.1	0	0	0.99	0.1	0	0
Not effective	0.01	0.99	0	0	0.1	0.9	0	0	0.01	0.9	0	0
No NVZ	0	0	1	1	0	0	1	1	0	0	1	1

The variable 'effectiveness of NVZ RBMP 1' (BN 11) has states of 'effective', 'not effective' and 'no measures', and is influenced by variables BN 15 and BN 08. The relationship of these variables to the states of BN 11 are represented in Table 5.16. The CPT reflects BN 11 state of 'effective' being positively favoured when existing programmes of measures are observed to be effective (BN 15), together with stakeholder compliance within the designated NVZ area (BN 08). Where 'non-compliance' by the stakeholders is observed it is assumed the NVZ designation is 'not effective'. This is based on Environment Agency data regarding the level of compliance of the farmers which are inspected under the implementation of the NVZ regulations. Monitoring data to identify the level of compliance of the farmers within the SPZs is limited, and therefore further observation of the land use activities within the designated areas could be additionally obtained for site specific conditions.

The variable 'uncontrolled diffuse sources in SPZ RBMP 1' (BN 14) has states of, 'yes' and 'no', and is influenced by variables BN 11 and BN 15. The relationship of these variables to the states of BN 14 are represented in Table 5.17. Whether diffuse sources of nitrate are uncontrolled (i.e. BN 14 state 'yes') or controlled (BN 14 state 'no') are determined by the range of protection measures in place resulting from the WFD and their effectiveness. Therefore where protection measures are 'effective', and NVZ is 'effective' BN 14 is assumed to have a high probability of 'no' uncontrolled diffuse sources of pollution within the SPZ. Where the NVZ (BN 11) is 'not effective' and the presence of uncontrolled diffuse pollution where protection measures (BN 15) are also 'effective', the probability is reduced to 0.5 for the presence of uncontrolled diffuse pollution when protective measure are in place (BN 15). Where the protection measures (BN 15) are either 'not effective' or absent for the SPZ there is a high probability of uncontrolled diffuse pollution being present. Further to this, where no NVZ has been designated (BN 11), this is based on the assumption that the risk of nitrate contamination within the water body is deemed to be low, therefore the probability of the presence of uncontrolled diffuse sources is also considered to be low. The reasoning for the CPT for diffuse nitrate pollution (BN 14) is assumed to be consistent with the CPT for point source nitrate pollution (BN 12) in this Bayesian network, although the respective CPT is presented for completeness in Table 5.18.

Table 5.17: CPT for 'Uncontrolled diffuse sources in SPZ RBMP 1' (BN 14)

Effectiveness of nitrate protection measures RBMP 1	*Effective*			*Not effective*			*No measures*		
Effectiveness of NVZ RBMP 1	*Effective*	*Not effective*	*No NVZ*	*Effective*	*Not effective*	*No NVZ*	*Effective*	*Not effective*	*No NVZ*
Yes	0.1	0.5	0.2	0.5	0.9	0.6	0.4	0.9	0.1
No	0.9	0.5	0.8	0.5	0.1	0.4	0.6	0.1	0.9

Table 5.18: CPT for 'Uncontrolled point sources in SPZ RBMP 1' (BN 12)

Effectiveness of nitrate protection measures RBMP 1	*Effective*			*Not effective*			*No measures*		
Effectiveness of NVZ RBMP 1	*Effective*	*Not effective*	*No NVZ*	*Effective*	*Not effective*	*No NVZ*	*Effective*	*Not effective*	*No NVZ*
Yes	0.1	0.5	0.2	0.5	0.9	0.6	0.4	0.9	0.1
No	0.9	0.5	0.8	0.5	0.1	0.4	0.6	0.1	0.9

Table 5.19: CPT for 'Risk of GW pollution 2010-15' (BN 13)

Uncontrolled diffuse source of nitrate in SPZ RBMP 1	*Yes*				*No*			
Uncontrolled point sources of nitrate in SPZ RBMP 1	*Yes*		*No*		*Yes*		*No*	
GW vulnerability to nitrate contamination	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
High	0.99	0.2	0.6	0.1	0.6	0.2	0.1	0.01
Low	0.01	0.8	0.4	0.9	0.4	0.8	0.9	0.99

Table 5.20: CPT for 'Groundwater at risk of failure of WFD objectives by 2015' (BN 19)

Current raw water quality (nitrate concentration)	*< 45 mg/l*						*> 45 mg/l*					
Current trend of GW quality (nitrate concentration)	*upward*		*stable*		*decreasing*		*upward*		*stable*		*decreasing*	
Existing risk of GW nitrate pollution	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*	*High*	*Low*
High	0.7	0.5	0.5	0.1	0.2	0.01	0.99	0.7	0.7	0.5	0.6	0.4
Low	0.3	0.5	0.5	0.9	0.8	0.99	0.01	0.3	0.3	0.5	0.4	0.6

The variable 'risk of the presence of GW nitrate pollution 2010-15' (BN 13) has states of, 'high' and 'low', and is influenced by variables BN 12, BN 14 and 'GW vulnerability to contamination' (BN 23, see Section 5.4.7). The relationship of these variables to the states of BN 13 are represented in Table 5.19. The CPT is based on the logic of the presence of pollution through both uncontrolled diffuse and point sources combined, where a vulnerable groundwater source presents the highest probability of being at risk (0.99). The lowest probability of the GW being at risk of pollution is the combination of no diffuse or point source contaminants, together with the groundwater not being vulnerable to contamination (0.01).

The variable ‘groundwater at risk of failure of WFD objectives by 2015’ (BN 19) has states of, ‘high’ and ‘low’, and is influenced by variables ‘existing risk of nitrate pollution’ (BN 06), ‘current trend of nitrate concentration in GW quality’ (BN 24, see Section 5.4.7) and ‘current nitrate concentration in raw water quality’ (BN 25, see Section 5.4.7). The relationship of these variables to the states of BN 19 are represented in CPT represented in Table 5.20. The CPT is based on the assumptions that the highest risk is posed where the existing water body has a nitrate concentration above 45 mg/l, with evidence of an upward trend of nitrate contamination in the groundwater, combined with the presence of existing risk of GW nitrate contamination. Conversely the lowest risk is presented where the existing water quality is not above 45 mg/l of nitrate, has a decreasing nitrate contamination trend, and the existing risk of nitrate contamination is low. Where there is a decreasing trend in nitrate concentration, the additional presence of an existing risk of nitrate pollution has a marginal impact on the probability, due to the predominance of the decreasing nitrate concentration trend. It is recognised that several other tests are also required to determine the failure of WFD objectives for groundwater (e.g. saline intrusion, impact of abstraction on surface water, groundwater dependent ecosystems, and water balance) although these are not considered within the boundaries of this system representation.

In subsequent RBMP implementation periods 2 and 3, the probability distributions within the CPTs are assumed to be the same for the respective components within the BN. When further data becomes available during the RBMP planning period these distributions can be updated to reflect the latest data for the management of the catchment at Barrow.

5.4.7 Barrow BN component 2: The physical environment

The physical environment is represented by the conditions related to the groundwater source whilst also considering the current quality of the water (in relation to the nitrate concentration), and the trend of water quality (with respect to the concentration of nitrate) and is depicted in Figure 5.19.

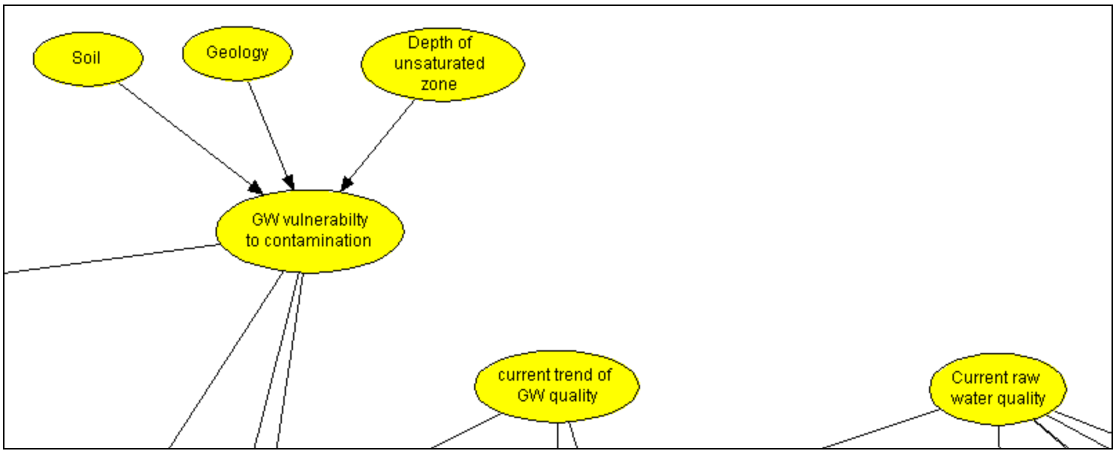

Figure 5.19: Bayesian network variables related to the physical environment component

The parent nodes of 'soil permeability' (BN 20), 'geology type' (BN 21) and 'depth of unsaturated zone' (BN 22) influence the vulnerability of the 'GW to nitrate contamination' (BN 23) (EA, 2010). The soil permeability (BN 20) has the states of 'high permeability' or 'low permeability', based on the soil types identified by the Hydrology of Soil Types (HoST) classification (Boorman *et al.*, 1995). The soil type for the Barrow catchment has a high permeability due to the characterisation of the soil as 'Hunstanton 571r' which is regarded as a deep, well-drained soil. It is specifically noted to have a 'high permeability' above chalky substrates. The geology type (BN 21) has states of 'chalk' or 'other', which represents the dominant type of geology across the Anglian region being chalk, including at Barrow. The depth of the unsaturated zone (BN 22) has states of 'shallow' and 'deep' and is an indicator of the distance a contaminant has to travel to reach the groundwater source. Across the Anglian region the depth of the unsaturated zone ranges between 0 to 230 meters below datum point (mbd), with 51% considered to be less than 20 mbd (AWS borehole asset data, 2010). Therefore the states of 'shallow' are defined by boreholes < 20mbd and 'deep' are defined as being > 20 mbd. At Barrow, the borehole is < 20mbd, and therefore ‘shallow’ is selected for the condition of BN 22.

The CPT for BN 23 and hence the relationships between the identified variables is presented in Table 5.21, although limited data exist to represent the detail of these relationships. In the BN constructed the probabilities have been informed by the EA guidance for the protection of groundwater (EA, 2010). It is assumed for Barrow that a shallow unsaturated zone, would result in contamination reaching the groundwater quickly, with an even greater risk of contamination where the geology is chalk which is covered with a high permeability soil type. These assumptions are reflected in the conditional probabilities in Table 5.21.

Table 5.21: CPT for ‘Groundwater vulnerability to contamination’ (BN 23)

Soil permeability	*High permeability*				*Low permeability*			
Geology type	*Chalk*		*Other*		*Chalk*		*Other*	
Depth of unsaturated zone	*Shallow*	*Deep*	*Shallow*	*Deep*	*Shallow*	*Deep*	*Shallow*	*Deep*
Yes	0.99	0.9	0.6	0.4	0.8	0.7	0.4	0.3
No	0.01	0.1	0.4	0.6	0.2	0.3	0.6	0.7

The two parent variables ‘current nitrate concentration trend in GW quality’ (BN 24) and ‘current nitrate concentration in raw water quality’ (BN 25) are also included in the baseline physical environment characterisation. BN 24 has states of ‘upward’, ‘stable’, and ‘decreasing’ to reflect the trend in the concentration of nitrate within the groundwater. These states represent the potential “at risk” classification of the water body used in the WFD implementation to inform the status of, and hence the performance of, water bodies against the WFD objectives. At Barrow the state of BN24 has an ‘upward’ trend due to the historical level of nitrate pollution present within the groundwater body. The variable BN 25 has states of ‘<45mg/l’ and ‘>45 mg/l’ for nitrate concentration. These are aligned with the internal Anglian Water standard, where water detected with >45mg/l of nitrate results in water being restricted for potable use, without further treatment. The existing water quality is > 45 mg/l of nitrate for the Barrow borehole sources, informed using site monitoring data, therefore the state of BN 25 is designated as > 45 mg/l. Both BN 24 and BN 25 influence ‘groundwater at risk of failure of WFD objectives by 2015’ (BN 19), and ‘blending used’ (BN 26) (see Section 5.4.8). In addition BN 25 also influences the nitrate concentration as indicated within the following variables, 'blended water quality' (BN 29), 'Ion exchange used' (BN 30), and 'processed water quality' (BN 31) (see Section 5.4.8). To inform future GW quality nitrate concentration trends in 2015, BN 24 and BN 25 also directly influence the nitrate concentration 'trend in GW quality in 2015' (BN 33) and 'GW quality in 2015' (BN 34) (Figure 5.20). The CPT for these relationships is presented in Table 5.22 and Table 5.23.

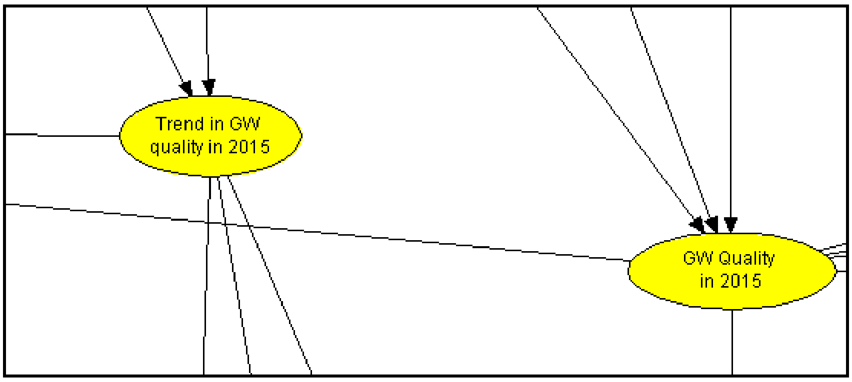

Figure 5.20: Bayesian network variables 'Trend in groundwater quality in 2013' (BN33) and 'Groundwater quality in 2015' (BN34)

Table 5.22: CPT for 'Trend in GW quality in 2015' (BN 33)

Existing risk of GW nitrate pollution	*High*			*Low*		
Current trend of GW quality (nitrate concentration)	*Upward*	*Stable*	*Decreasing*	*Upward*	*Stable*	*Decreasing*
Upward	0.9	0.6	0.5	0.2	0.05	0.05
Stable	0.05	0.35	0.3	0.3	0.35	0.05
Decreasing	0.05	0.05	0.2	0.5	0.6	0.9

Table 5.23: CPT for 'Groundwater quality in 2015' (BN 34)

Current raw water quality (nitrate concentration)	*< 45 mg/l*						*> 45 mg/l*					
Existing risk of GW nitrate pollution	*High*			*Low*			*High*			*Low*		
Current trend of GW quality (nitrate concentration)	*Upward*	*Stable*	*Decreasing*	*Upward*	*Stable*	*Decreasing*	*Upward*	*Stable*	*Decreasing*	*Upward*	*Stable*	*Decreasing*
< 45 mg/l	0.6	0.7	0.8	0.9	0.9	0.99	0.01	0.1	0.1	0.2	0.3	0.4
> 45 mg/l	0.4	0.3	0.2	0.1	0.1	0.01	0.99	0.9	0.9	0.8	0.7	0.6

In Table 5.22, the CPT for the nitrate concentration 'trend in GW quality in 2015' (BN 33) reflects that the CPT is directly influenced by an 'existing nitrate concentration trend’ (BN 24) for water quality and the ‘existing risk of groundwater nitrate pollution’ (BN 06). For example, where the current water quality has an ‘upward’ trend of nitrate concentration and there is also a high risk of existing nitrate pollution, the CPT therefore reflects that the future trend in 2015 for water quality will have a high probability (0.9) of remaining on an ‘upward’ trend in nitrate concentration. Conversely a ‘low’ risk of existing nitrate pollution (BN 06) combined with an evident ‘decreasing’ nitrate trend (BN 24) would indicate the highest probability for a ‘decreasing’ nitrate trend in groundwater quality into the future (BN 33). The conditional probabilities indicated in Table 5.22 are assumed to be constant, within this Bayesian network for the determination of the future nitrate concentration trends in groundwater for subsequent time periods.

Table 5.23, presents the CPT for ‘groundwater quality in 2015’ (BN 34). This CPT is based on the assumption that where ‘current raw water quality’ (hence nitrate concentration) (BN 25) is > 45 mg/l, combined with the presence of a ‘high’ risk of ‘existing groundwater nitrate pollution’ (BN 06) as well as an ‘upward’ trend of nitrate contamination in the water (BN 24), there is a ‘very likely’ (i.e. 0.99) probability of nitrate contamination in ‘future groundwater quality’ (BN 34) being > 45 mg/l. Conversely where the nitrate concentration in the ‘current raw water quality’ (BN 25) is < 45 mg/l, with a ‘low’ risk of ‘existing pollution’ (BN 06), as well as a ‘decreasing’ trend in water quality (hence nitrate contamination) (BN 24) a ‘very unlikely’ (i.e. 0.01) probability is assumed for the nitrate concentration within the ‘groundwater quality in 2015’ (BN 34) being > 45 mg/l. Where a ‘high’ risk of further nitrate pollution in groundwater is present, the impact of the probability of the nitrate concentration in ‘future groundwater quality’ being > 45 mg/l where ‘existing water quality’ has a nitrate concentration of < 45 mg/l is assumed to be ‘not probable’ (i.e. 0.2). Conversely where a ‘low’ risk of ‘further nitrate pollution of groundwater’ is present, with ‘current raw water quality’ having a nitrate concentration of > 45 mg/l, and a ‘decreasing’ trend in nitrate contamination within the water, a probability of 0.6 is assumed. This reflects the reduced probability of the future water quality having a nitrate concentration of > 45 mg/l due to the reduction in the risk of further nitrate contamination entering the groundwater.

5.4.8 Barrow BN component 3: Management of potable water

The variables representing the management of potable water treatment in response to the changes in the nitrate concentration of raw water quality and the trends in raw water quality are depicted in Figure 5.21. This is a parsimonious representation of the variables for potable water management.

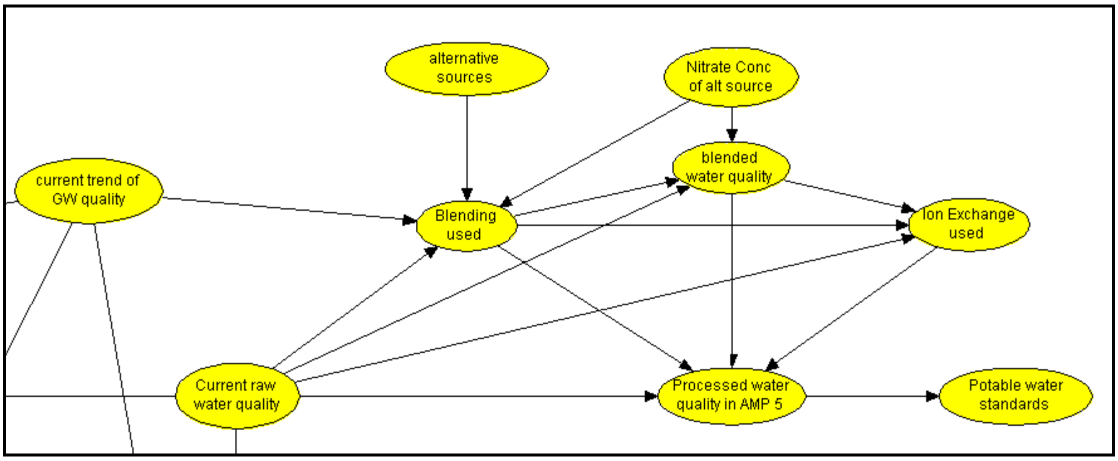

Figure 5.21: Bayesian network variables for the management of potable water supply component

Details related to the variables 'current water quality' (BN 25) and 'current trend' (BN 24) in relation to nitrate concentration have been detailed in Section 5.4.7. The additional parent variables of the availability of 'alternative sources' (BN 27) and 'nitrate concentration of alternative source' (BN 28) are also now included. BN 27 introduces the option of blending water sources where alternative sources are available, and hence states of 'yes' and 'no' are used. Alternative sources, when available, are used to blend with water at Barrow to result in a reduction in nitrate concentration in the resultant blended water (BN 29), and hence avoid the need for treatment (BN 30). Barrow has access to alternative water supplies from three nearby groundwater sources (Thornton, Barton, and Goxhill). For simplicity, these sources have been considered as one combined source which is available as a blend option (although could be extended in a more complex BN to reflect the additional sources). BN 28 recognises the nitrate concentration in the alternative sources and has states of '< 45 mg/l' and '>45mg/l', which informs whether 'blending' (BN 26) can be used, whilst also influencing the nitrate concentration in the 'blended water quality' (BN 29).

Whether blending is used (BN 26) is determined by the states of BN 24, BN 25, BN 27 and BN 28. The relationship between these variables and respective states are presented in the CPT for BN 26 shown in Table 5.24 and Table 5.25. (Note: Due to the size of the CPT, it has been presented using two tables, one presenting the conditional probabilities for 'current raw water quality' having a nitrate concentration of <45mg/l [Table 5.24], and one for being >45mg/l [Table 5.25]). The CPT for BN 26 has been based on informed judgement using the following assumptions. Where no 'alternative sources' (BN 27) are present, 'no' blending is used. Where the 'current raw water quality' (BN 25) is < 45 mg/l and an 'upward' trend of increasing nitrate contamination (BN 24) is present, 'alternative sources' are used, with a probability of 0.7, but only when the nitrate concentration of the alternative source (BN 28) is < 45 mg/l. Where the 'alternative source' is > 45 mg/l, it is considered to be 'less probable' that an 'alternative water source' which may further increase the nitrate concentration of the 'current raw water quality' (BN 25), will be used. Where a 'stable' trend for raw water quality (BN 24) has a nitrate concentration of < 45 mg/l, additional water from an alternative source is less likely to be required and hence has a probability of 0.1. Similarly, where a 'decreasing' trend, hence reduced nitrate contamination, is evident, it is assumed 'highly unlikely' that an alternative source is used. Where the nitrate concentration in 'raw water' (BN 25) is > 45 mg/l the use of 'alternative supplies' (BN27) which are < 45 mg/l are 'highly likely' with a probability of 0.99. Blending water has historically been used to reduce the overall nitrate concentration, although in the Barrow catchment, all 'alternative sources' (Barton, Goxhill, Thornton) now have an established upward trend of increasing nitrate concentration which is close to or above the 45 mg/l limit. The Thornton source is the only source which is considered to be < 45 mg/l, although by 2015 it is also expected to be > 45 mg/l. Therefore the use of blending as an option to reduce nitrate concentration is becoming increasingly less available as an option. The designation of blending as a management intervention is recognised through the application of scenarios and instantiated nodes in the subsequent sections in this chapter.

Table 5.24: CPT for 'Blending used' (BN 26) (where current raw water quality is < 45 mg/l)

Current raw water quality	*< 45 mg/l*											
Current trend of GW quality	*Upward*				*Stable*				*Decreasing*			
Alternative sources	*Yes*		*No*		*Yes*		*No*		*Yes*		*No*	
Nitrate concentration of alternative sources	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*
Yes	0.7	0.01	0	0	0.1	0.01	0	0	0.01	0.01	0	0
No	0.3	0.99	1	1	0.9	0.99	1	1	0.99	0.99	1	1

Table 5.25: CPT for 'Blending used' (BN 26) (where current raw water quality is > 45 mg/l)

Current raw water quality	*> 45 mg/l*											
Current trend of GW quality	*Upward*				*Stable*				*Decreasing*			
Alternative sources	*Yes*		*No*		*Yes*		*No*		*Yes*		*No*	
Nitrate concentration of alternative sources	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*	*< 45mg/l*	*> 45mg/l*
Yes	0.99	0.01	0	0	0.99	0.01	0	0	0.99	0.01	0	0
No	0.01	0.99	1	1	0.01	0.99	1	1	0.01	0.99	1	1

Table 5.26: CPT for 'Processed water quality' (BN 31)

Current raw water quality	*< 45 mg/l*								*> 45 mg/l*							
Blending used	*Yes*				*No*				*Yes*				*No*			
Blended water quality	*< 45 mg/l*		*> 45 mg/l*		*< 45 mg/l*		*> 45 mg/l*		*< 45 mg/l*		*> 45 mg/l*		*< 45 mg/l*		*> 45 mg/l*	
Ion exchange used	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
< 45 mg/l	0.99	0.99	0.99	0.1	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.01	0.99	0.01	0.99	0.01
> 45 mg/l	0.01	0.01	0.01	0.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.99	0.01	0.99	0.01	0.99

'Blended water quality' (BN 29) refers to the nitrate concentration of the blended water and has states of '< 45 mg/l' and '> 45 mg/l'. BN 29 is influenced by BN 25, BN 26, and BN 28 and the relationship between these variables and states are depicted in Table 5.27. The CPTs are based on the assumption that when both the 'raw water quality' (BN 25) and the 'alternative source of water' (BN 27) are < 45 mg/l, a 'high' probability is assumed that the resulting 'blended water' (BN 29) would be < 45 mg/l. When the 'raw water quality' has a nitrate concentration of > 45 mg/l in addition to the 'alternative source' being > 45 mg/l, a 'high' probability of the resulting blend water being > 45 mg/l is also is assumed, although these instances would occur infrequently. Where the 'current raw water' has a nitrate concentration of < 45 mg/l, and 'blending is used' (BN 26) with water which is > 45 mg/l, it is assumed that there is an increased probability of the resulting 'blend water' (BN 29) being > 45 mg/l. Where the 'raw water' (BN 25) is > 45 mg/l is blended with an 'alternative source' which is < 45 mg/l an equal probability distribution between the states is assumed, reflecting the uncertainty in the amount of water required as a diluting factor to reduce the current nitrate concentration in the water

Table 5.27: CPT for 'Blended water quality' (BN 29)

Current raw water quality	*< 45 mg/l*				*> 45 mg/l*			
Nitrate concentration of alternative source	*< 45mg/l*		*> 45mg/l*		*< 45 mg/l*		*> 45mg/l*	
Blending used	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
< 45 mg/l	0.99	0.99	0.8	0.99	0.5	0.01	0.01	0.01
> 45 mg/l	0.01	0.01	0.2	0.01	0.5	0.99	0.99	0.99

The variables 'Ion exchange used' (BN 30) is dependent on BN29, BN 26, and BN 25, and has states of 'yes' or 'no'. In AMP 4 ion exchange is used at the site, and subsequently the node (BN 30) is set to 'yes' for the baseline conditions. The relationship between BN 30 and its dependent variables and their states, into the future AMP periods, is reflected in the conditional probabilities in Table 5.28. When conditions of the 'blended water quality' (BN 29) and 'current water quality' (BN 25) are < 45 mg/l there is no requirement for ion exchange. When either the 'current water quality' is > 45 mg/l or when 'blending is used', the resultant 'blended water quality' (BN 29) is > 45 mg/l, and consequently ion exchange treatment is required. The information used to determine these relationships are based on the site observations, discussions with site managers (ID23, ID42, ID78) and regulatory requirements to ensure potable water quality standards for nitrate are met.

Table 5.28: CPT for ‘Ion exchange used’ (BN 30)

Current raw water quality	*<45mg/l*				*> 45mg/l*			
Blending used	*Yes*		*No*		*Yes*		*No*	
Blended water quality	*<45 mg/l*	*>45 mg/l*	*<45 mg/l*	*>45 mg/l*	*<45 mg/l*	*>45 mg/l*	*<45 mg/l*	*>45 mg/l*
Yes	0.01	0.99	0.01	0.01	0.2	0.99	0.99	0.99
No	0.99	0.01	0.99	0.99	0.8	0.01	0.01	0.01

The ‘processed water quality’ (BN 31) CPT is presented in Table 5.26, which represents the relationships between the variables BN 25, BN 26, BN 29 and BN 30 and their respective states on BN 31. The regulatory requirement to meet the Drinking Water Directive (DWD) standards for potable water quality is considered to be a constraint on the performance of the treatment process. The processed water quality is assumed to have a nitrate concentration of < 45 mg/l, which is equivalent to the internal Anglian Water standard for potable supply. At 5 mg/l less than the DWD, it provides a safety margin to ensure potable water supply does not breach the potable water standards. The conditions which may result in the water quality being above the 45 mg/l limit with a probability of ‘very likely’ (i.e. 0.99) and ‘likely’ (i.e. 0.9) have been based on the following combinations of states; (i) a raw water quality with a nitrate concentration of < 45mg/l which is blended with an additional source which is > 45 mg/l, and no ion exchange is used, (ii) a raw water source with a nitrate concentration of > 45 mg/l with additional blending with a source which is > 45 mg/l, with no ion exchange treatment, (iii) a raw water source with a nitrate concentration of > 45mg/l where no blending or ion exchange is used.

The CPTs presented in these sections are replicated for the subsequent time steps within the BN, to provide consistency in interpretation of the relationships between the variables, and to provide a basis from which further data and information can be included into the future.

5.4.9 Scenario analysis (Step 2.16)

Once the set-up of the BN is complete, analysis can be conducted through the exploration of different scenarios. These can be conducted either as forward or backward propagated scenarios. A forward propagation is concerned with the probability of a specific outcome variable in a specific state, given the implementation of specific management decisions, policy interventions, or physical environmental conditions (e.g. the future condition of water quality due to restrictions in nitrate use on land). A backward propagated scenario on the other hand, can identify, working from a desired state of a specific outcome variable, the management option, policy decision or physical environmental conditions which would need to be in place in order for the specific outcome variable to be achieved (e.g. whether restriction on nitrate use on land would be the preferred or optimal management action to deliver the desired value for the outcome variable).

The scenarios used to inform management options for potable water at Barrow were conducted using forward propagation, and are described in Table 5.29. These include the 'baseline', 'worst case' and 'best case' scenarios. The states of the variables used to inform the baseline scenario are presented in Table 5.30, and each of the scenarios with the corresponding BN are presented in Figure 5.22, Figure 5.23 and Figure 5.24. The scenarios were assessed with regard to the raw water quality used for potable supply (BN 32) and the impact on ion exchange treatment (BN 30), with the probabilities associated with the states of these variables presented in Table 5.31. A Value of Information (VoI) was also conducted by the researcher to explore where further investment could reduce the uncertainties in the BN.

Table 5.29: Scenario overview

Scenario	Outline
Baseline	Baseline conditions with background data for current situation, combined with the current knowledge and understanding regarding the future states of the variables and the conditional relationships.
Worst case	Baseline conditions, with assumed non-compliance with future legislative measures to control nitrate pollution. All alternative sources of water are contaminated to above 45 mg/l. No AW catchment management considered.
Best Case	Compliance with all legislative measures to control nitrate, assumed through effective enforcement through the Environment Agency. AW catchment management is implemented across all RBMPs, assuming Ofwat recognise it as a viable investment option. Alternative blend water becomes < 45 mg/l after AMP 7 (based on the assumption of improved management of nitrate at Thornton and Goxhill through improved farm management practices as a result of catchment sensitive farming initiative combined with overall effective WFD measures across these respective SPZs.)

Table 5.30: Summary of the variables and the baseline conditions for Barrow.

BN Ref Number	Background condition nodes	State of variable	Baseline condition instantiated probability	Confidence (Ofwat, 2010b)	Data source
BN 20	Soil permeability	High permeability	1	A2	Based on Hydrology of soil type classification of soils within the SPZ 1. (Cranfield University, 2008)
BN 21	Geology	Chalk	1	A2	Barrow WTW Operational Manual (AWS, 2007b)
BN 22	Depth to unsaturated zone	Shallow	1	A3	Depth of unsaturated zone is 15 mbd, which is less that 20 m used to classify the state of shallow within the network. (AWS data for Barrow borehole within site spreadsheet).
BN 24	Current trend of groundwater quality	Upward	1	A1	Anglian Water monitoring data from Barrow combined boreholes, where a baseline trend of 1.00 mg/l/a recorded since 1981. (from Crystal QD Warehouse).
BN 25	Current raw water status	> 45 mg/l	1	A1	Anglian Water monitoring data, based on an average concentration of nitrate in all four boreholes for Barrow being above 79 mg/l from 2007 with minimum of 73 mg/l (2008) and a maximum of 11 mg/l (2008).
BN 02	Existing NVZ designation	Designated	1	A1	Defra Nitrate Vulnerable Zone Map (Defra, 2009)
BN 01	Stakeholder NVZ compliance	Non-compliant	0.8	B4	Site observation of nitrate management within SPZ (e.g. manure piles within fields, livestock within SPZ)
BN 16	Drinking Water Protection Area designation in RBMP 1	Designated	1	A1	RBMP 1, (EA, 2009b)
BN 17	Safeguard Zone designation in RBMP 1	Designated	1	A1	RBMP 1 , (EA, 2009b)
BN 10	NVZ designation in RBMP 1	Designated	1	A1	RBMP 1, (EA, 2009b)
BN 27	Alternative sources available (source from Barton, Goxhill and Thornton)	Yes	1	A2	The three additional sources available are considered to be combined as one input option within this network. (AWS, 2007b)
BN 28	Nitrate concentration of alternative source (combined sources from Barton, Goxhill and Thornton)	> 45 mg/l	1	A2	Anglian Water monitoring data (Crystal QD Warehouse)
BN 30	Ion exchange used	yes	1	A1	Operational on site (AWS, 2007b)
BN 26	Blending used	yes	1	A1	Operational on site (AWS, 2007b)

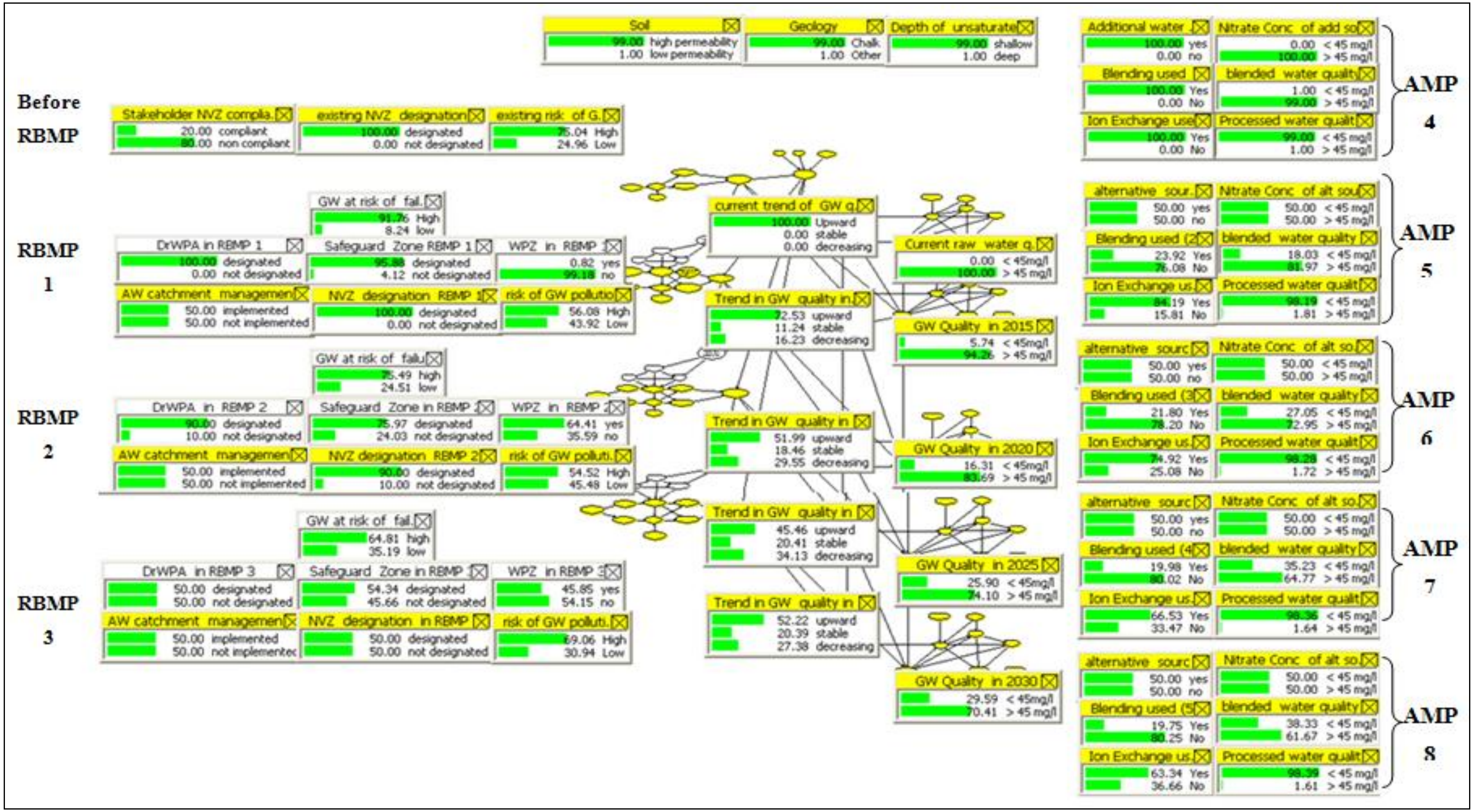

Figure 5.22: Baseline BN for Barrow

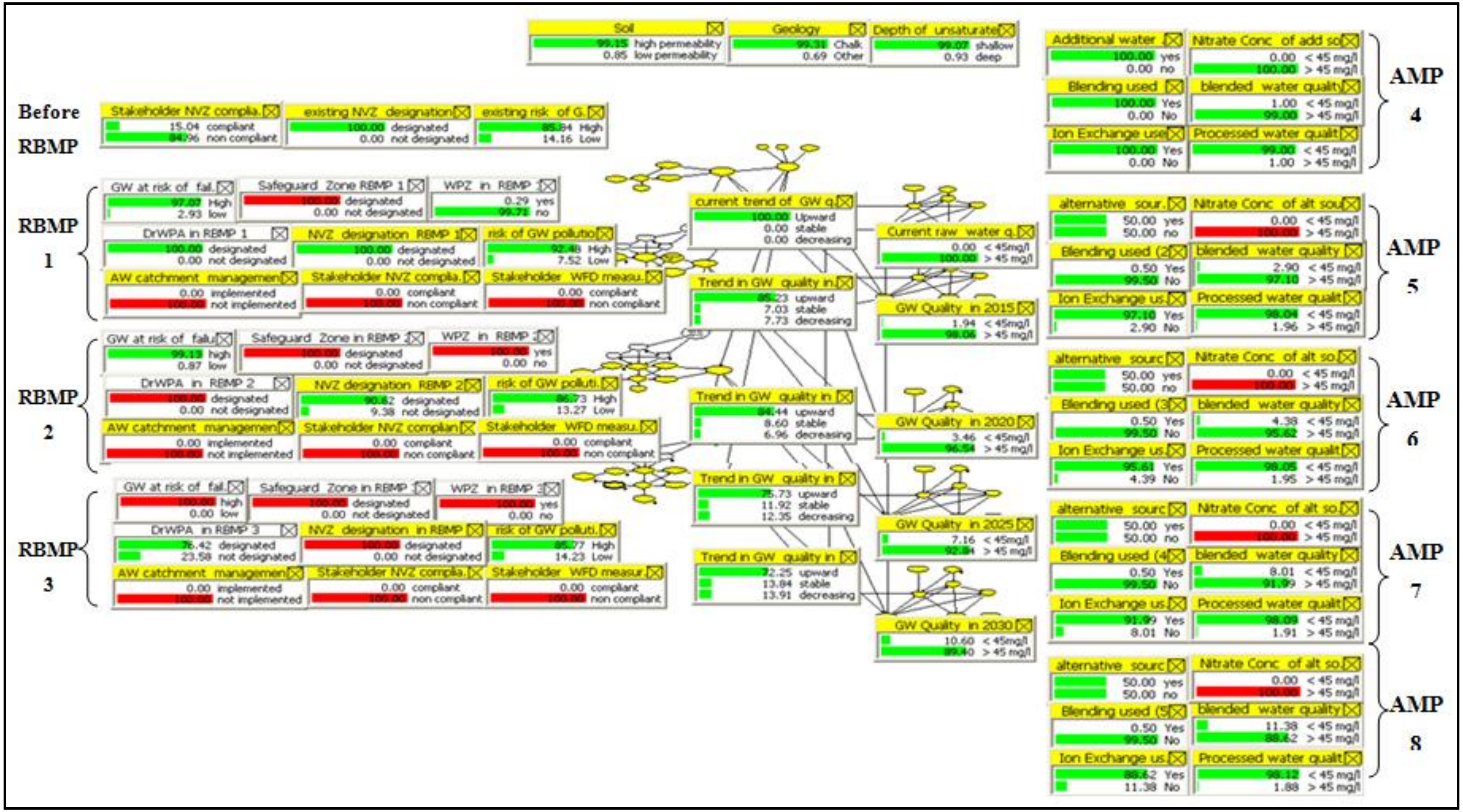

Figure 5.23: Worst case scenario for Barrow catchment and treatment

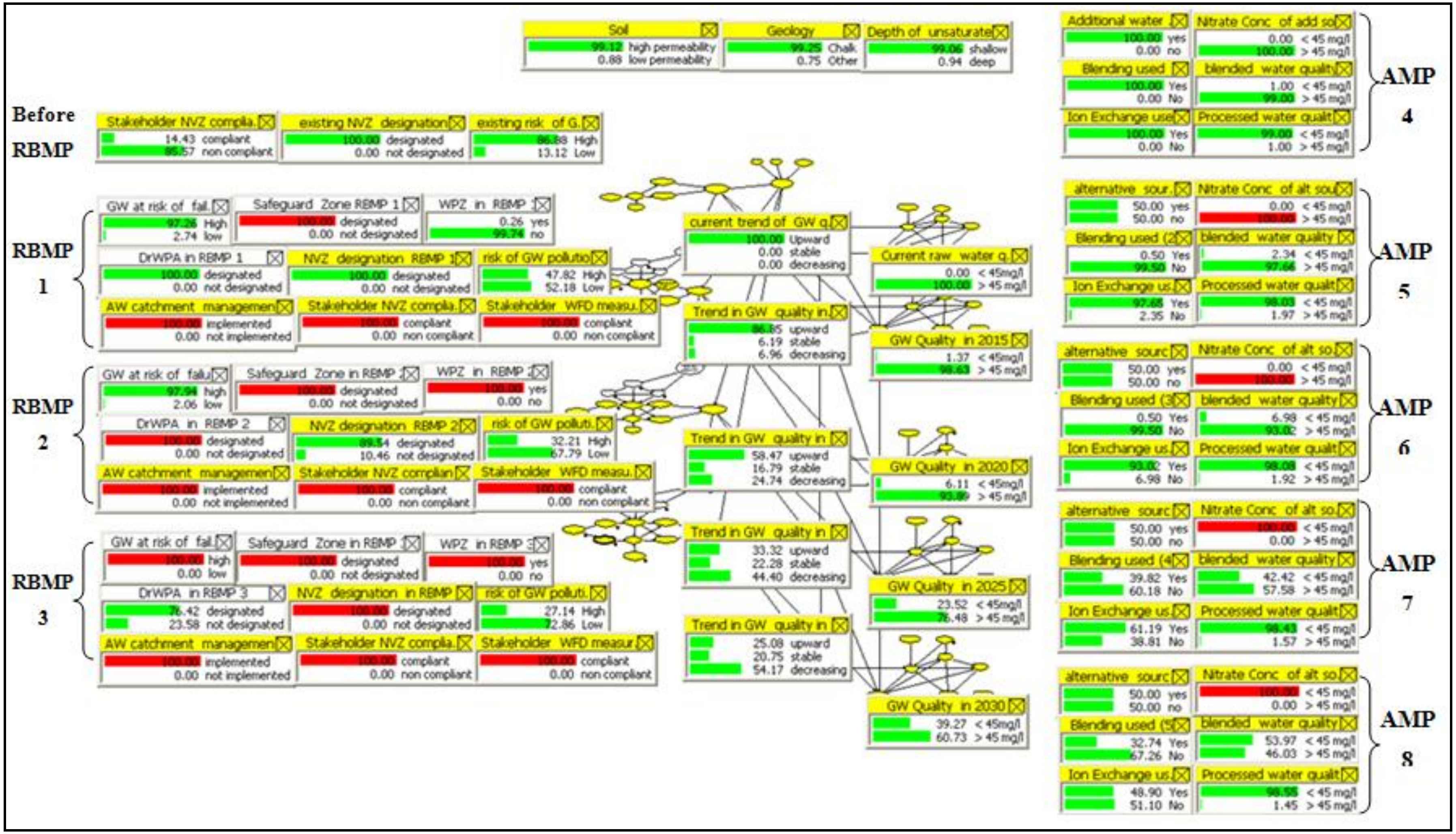

Figure 5.24: Best case scenario for Barrow catchment and treatment

Table 5.31: Summary table of output probabilities for key variables to determine strategy development for potable water supply

	Probability(%) associated with each state of the respective variables for the three scenarios.					
Output variable	***Scenario 1: Baseline***		***Scenario 2: Worst Case***		***Scenario 3: Best Case***	
State of variable	*< 45 mg/l*	*> 45mg/l*	*< 45 mg/l*	*> 45mg/l*	*< 45 mg/l*	*> 45mg/l*
Raw water quality 2010	0	100	0	100	0	100
Raw water quality 2015	5.74	94.26	1.94	98.06	1.37	98.63
Raw water quality 2020	16.31	83.69	3.46	96.54	6.11	93.89
Raw water quality 2025	25.9	74.10	7.16	92.84	23.52	76.48
Raw water quality 2030	29.59	70.41	10.6	89.40	39.27	60.73
State of variable	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Ion exchange used AMP 4	100	0	100	0	100	0
Ion exchange used AMP 5	84.19	15.81	97.1	2.9	97.65	2.35
Ion exchange used AMP 6	74.92	25.08	95.61	4.39	93.02	6.98
Ion exchange used AMP 7	66.53	33.47	91.99	8.01	61.19	38.81
Ion exchange used AMP 8	63.34	36.66	88.62	11.38	48.90	51.10

In Table 5.31 the output variable of ‘raw water quality’ over the successive five AMP cycles is presented for each of the three scenarios. In the worst case scenario, the probability of the raw water having a nitrate concentration of > 45 mg/l by 2030 is 89%, whereas for the best case scenario this probability drops to 60%. Therefore under the conditions and assumptions used in this dynamic BN, the water used for potable supply will still require ion exchange treatment by 2030, even with the best case scenario. This is reflected in the probability of the requirement for ion exchange treatment in the best case scenario being equally likely. The probabilities resulting from the scenarios run for the ‘raw water quality’ output variable can then be fed into Asset Plus+ as a ‘Pre-Investment’ service measure assessment (for the baseline scenario with no investment), and a ‘Post-Investment’ service measure assessment for the best case scenario (where AWS interventions are used). These probabilities would then update the risk assessment for the performance of the water treatment assets and recalculate the proposed investment requirements. (During the period of this research the use of the probabilities in this demonstration informing Asset Plus+ was not able to be achieved due to time and resource constraints).

Value of Information analysis for Barrow

Using the Value of information analysis function within the Hugin A/S Expert software the value of reducing the uncertainty associated with the ‘risk of GW nitrate pollution in 2015-2021’ was calculated and presented in Figure 5.25. Hence, further investment in understanding the control of diffuse and point sources in the SPZ was identified as the most valuable information to acquire to reduce the level of uncertainty for the ‘risk of GW pollution in 2015-2021’ variable.

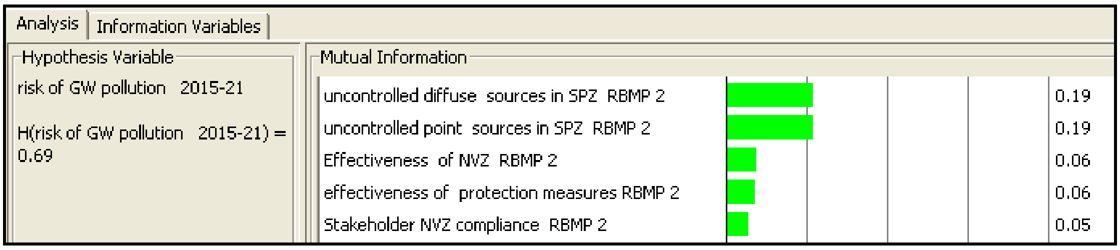

Figure 5.25: VoI analysis for risk of GW pollution

To determine what information would be of most value to reduce the uncertainty of the ‘uncontrolled diffuse source of nitrate pollution in SPZ 2’ variable (i.e. during RBMP cycle 2 2015-2021), investment in identifying the ‘effectiveness of NVZ’ within the catchment during the period of RBMP 2, together with the ‘effectiveness of the nitrate protection measures’ implemented within RBMP 2 is identified in Figure 5.26.

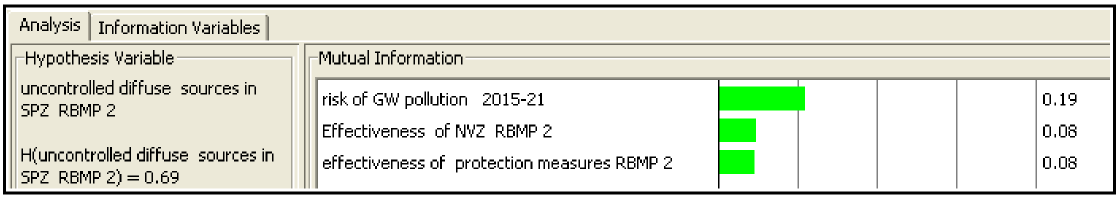

Figure 5.26: VoI analysis for uncontrolled diffuse sources in SPZ RBMP 2

This value of information analysis supports the organisational responses identified in Phase 1 Step 1.13 and Phase 2 Step 2.2 which include ‘research into aquifer responses to pollution’ (R3), ‘investment to target the cause of potable water sources of nitrate pollution’ (R7), ‘educate and raise awareness of farmers of nitrate pollution’ (R1A), and ‘monitor the effectiveness of implementation of legislation’ (R16).

5.4.10 Strategic options (Step 2.17)

The investment options identified from Phase 1 and Phase 2 were cross referenced with organisational strategic priorities to highlight how the options relate to the overarching strategic objectives of the water company outlined within the new 25 year Strategic Direction Statement (SDS) (AW, 2007a). Table 5.33 provides a qualitative analysis of the relationship between Phase 1 generic responses (R1 – R16) and the Phase 2 site specific responses (i) the important site specific stakeholders identified in Step 2.6 (‘key players’ and ‘context setters’ in Table 5.32), (ii) site specific organisational responses (from Step 2.7), (iii) site specific treatment responses (Step 2.15) and (iv) key evidence to be obtained to reduce the uncertainty in hypothesis variables (e.g. raw water quality) within the BN (Step 2.15), to identify how the site specific responses align with the generic responses. Table 5.34 provides a qualitative assessment of the alignment of the proposed organisational responses to the strategic organisational priorities and service delivery measures. The site specific organisational requirements are also qualitatively assessed by the researcher based on informed judgement regarding the organisation and personal insights into operating conditions for the site, to identify the alignment with the organisational strategic priorities and therefore further integrated with the organisation strategy development (Table 5.35 and Table 5.36).

Table 5.32: Key stakeholder relationships to develop

Stakeholders Identified	Supportive (+)	Neutral (o)	Unsupportive (-)	Stakeholder classification
Agricultural Suppliers		o		**Key Player**
Agrochemical Industry		o		**Key Player**
Anglian Water	+			**Key Player**
Biofuel producers		o		**Key Player**
Catchment Sensitive Farming Officers	+			**Key Player**
DEFRA	+			**Key Player**
Drinking Water Inspectorate	+			**Key Player**
Environment Agency	+			**Key Player**
Environment Agency - Regional	+			**Key Player**
European Commission	+			**Key Player**
Farmers		o		**Key Player**
Local Government		o		**Key Player**
Local Press		o		**Key Player**
National Farmers Union	+			**Key Player**
National Government	+			**Key Player**
Natural England	+			**Key Player**
Nature Conservation Groups	+			**Key Player**
OFWAT	+			**Key Player**
Other Water Companies*	+			**Key Player**
Regional Government	+			**Key Player**
Supermarkets		o		**Key Player**
Industry (Business customers)		o		**Context Setters**
Land owners		o		**Context Setters**
Water UK	+			**Context Setters**

Table 5.33: Cross-reference matrix for the general organisational responses identified in Phase 1 and the site specific responses identified in Phase 2

		Organisational responses identified in Phase 1 Step 1.13															
Phase 2 analysis activities	**Phase 2 site specific organisational responses**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**
Step 2.6 Stakeholder analysis	Engagement with **key players** and **context setters** as identified in the Stakeholder analysis	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Step 2.7 Causal analysis *(additional site specific responses)*	Liaise directly with farmers in SPZ to educate and raise awareness of nitrate pollution (R1A)	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
	Workshop with local stakeholders regarding GW pollution (R2A)				✓	✓	✓	✓		✓	✓		✓		✓	✓	
	Data sharing with stakeholders (R3A)	✓		✓	✓	✓	✓			✓	✓		✓		✓	✓	
Step 2.15 Bayesian network analysis	Ion Exchange treatment requirements for Barrow	✓	✓			✓										✓	
Step 2.16 VoI: variables requiring further information	Increased information required for 'risk of GW pollution 2015-2021'	✓		✓	✓	✓	✓		✓	✓							✓
	Increased information required for 'uncontrolled diffuse sources in SPZ RBMP 2'								✓	✓	✓		✓				✓
	Increased information required for 'uncontrolled point sources in SPZ RBMP 2'								✓	✓	✓		✓				✓

Note: Descriptions of R1 – R16 provided in Table 5.1.

Table 5.34: Qualitative assessment of the alignment of the proposed organisational responses to the strategic organisational priorities and service delivery measures

	Organisational strategic priorities (AWS, 2007a)							***Service delivery measure****
Strategic organisational response options**	**Increase the resilience and reliability of our water and wastewater services**	**Secure and conserve water resources**	**Anticipate and invest for growth in our region**	**Improve the environment in our region**	**Mitigate and adapt to climate change impacts**	**Improve our efficiency and flexibility**	**Keep bills at current affordability**	**Physiochemical water quality failure** (e.g. nitrate)
R1	✓	✓	✓	✓	✓	✓		✓
R2	✓	✓			✓	✓		✓
R3	✓	✓		✓	✓	✓		✓
R4	✓	✓		✓	✓	✓		✓
R5	✓	✓	✓	✓	✓	✓	✓	✓
R6	✓	✓	✓	✓	✓	✓	✓	✓
R7	✓	✓		✓	✓	✓	✓	✓
R8	✓	✓	✓	✓	✓	✓		✓
R9	✓	✓	✓	✓	✓	✓	✓	✓
R10	✓	✓	✓	✓	✓	✓	✓	
R11	✓	✓	✓		✓	✓	✓	
R12	✓	✓		✓	✓	✓	✓	✓
R13	✓	✓	✓	✓	✓	✓	✓	✓
R14	✓	✓	✓	✓	✓	✓	✓	✓
R15	✓	✓	✓	✓	✓	✓	✓	
R16	✓	✓				✓		✓

Note   * *service delivery measure for reasons for failure of water non-infrastructure (above ground) assets (AWS, 2009b)*

***Water Company responses to support organisational strategy from Phase 1.13 and address water infrastructure and non-infrastructure service measures (Descriptions of R1 – R16 provided in Table 5.1.)*

Table 5.35: Site specific investment requirements for each scenario

Scenario	Site Specific investment requirements to ensure potable water standards are met
Best Case	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, although it is reducing to a 60% probability, by 2030. Investment in catchment management activities (R1A, R2A, R3A) to influence the reduction of nitrate pollution at the catchment level, through stakeholder engagement, data sharing, education and awareness raising with local stakeholders.
Baseline	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, although it is reducing to a 70% probability, by 2030. Initial investment in Catchment Management for RBMP 1.
Worst case	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, with a probability of 89% by 2030.

Table 5.36: Qualitative assessment of the investment requirements identified and their alignment with the strategic priorities and service measures.

Scenario	Organisational strategic priorities (AWS, 2007a)							Service delivery measure*
	Increase the resilience and reliability of our water and wastewater services	Secure and conserve water resources	Anticipate and invest for growth in our region	Improve the environment in our region	Mitigate and adapt to climate change impacts	Improve our efficiency and flexibility	Keep bills at current affordability	Physiochemical water quality failure (e.g. nitrate)
Best Case	✓	✓		✓				✓
Baseline	✓			✓				✓
Worst case	✓							✓
Note	* service delivery measure for reasons for failure of water non-infrastructure (above ground) assets (AWS, 2009b)							

More detailed quantitative analysis of the likely timing of investment requirements for future treatment at Barrow can be achieved through manual input of the probability of the condition of the raw water quality used for potable supply, into the Asset Plus + investment management system within Anglian Water. This allows for the updating of the risk profile associated with the performance of the asset (Ion Exchange), which would inform the appropriate timing of investment into the future. This was not conducted for Barrow, although based on the analysis through the BN the requirement for treatment under all three scenario's (based on the assumptions within the network) will still be required by 2030. Therefore investment in catchment management as a preventative measure will not necessarily be evidenced by any changes in raw water quality, over the time period considered, due to the highly contaminated nature of the groundwater body.

5.4.11 Results from Phase 2

The analysis conducted for the specific site and pressure for potable water management has highlighted several points:

Step 2.1-2.3:

- Pressure specific factors were identified to be political, social and environmental and emphasis was on targeting the management of the potable water supply chain and the catchment level.
- Stakeholders were identified to be similar to Phase 1

Step 2.4-2.5:

- Response factors were identified as WFD specific and organisation specific as well as general responses to target the pressure of nitrate at the site of Barrow.

Step 2.6:

- Specific stakeholders were identified to be engaged with as an organisational response include: the agrochemical industry, environmental regulators, and farmers.

Step 2.7:

- A DPSIR Grid was created to visually identify which "responses" are used to target the management of the "pressure" through the D-P-S-I chain. Therefore a visual map of all the organisational responses, WFD responses and existing responses was generated to inform where any additional investments may be required.

Step 2.8-2.15:

- Factors were prioritised and consequently selected as variables to be included in the development of a BN. The BN was a dynamic BN over both six yearly cycles (RBMP) and five yearly cycles (AMP) and comprised of components related to the 'management of the catchment', the 'physical environment' and the 'management of potable water treatment'.

Step 2.16:

- Best case, worst case and baseline scenarios were selected, and run within the BN. Under the most favourable conditions to manage nitrate within the catchment at Barrow, the probability of the raw water quality being less than 45mg/l by 2030 was only 39%. Therefore continued investment in treating nitrate at the site is needed.
- Subsequent identification of the Value of Information (VoI) analysis indicated resources should be focused on understanding the 'effectiveness of NVZ' within the catchment, and understanding the 'control of diffuse and point sources in the SPZ'.
- These responses identified from the VoI analysis support the organisational responses identified in Phase 1 which included:
  - research into aquifer responses to pollution (R3),
  - investment to target the cause of potable water sources pollution (R7),
  - educate and raise awareness of farmers (R1A),
  - monitor the effectiveness of implementation of legislation (R16).

Step 2.17:

- Matrices to cross-reference: site specific investment options with general organisational investment options; and cross- reference the site and general responses to organisational strategic objectives were generated. This alignment facilitates the development of a transparent organisational strategy in response to the implications of strategic environmental legislative changes affecting the management of potable water supply.

5.5 Summary

In this chapter the Hybrid-DSP has been demonstrated. The Hybrid-DSP has enabled an integrated qualitative assessment of the development and identification of organisational responses to the changes brought about through the WFD. The strategic options for consideration by the organisation are proposed at both the generic level from Phase 1, and with further site and pressure specific analysis during Phase 2. The combined strategic options generated were qualitatively assessed against the overall water company objectives, to ensure alignment with strategy development within subsequent AMP periods would be understood. The outputs from the Hybrid-DSP and the use of the Hybrid-DSP are discussed in Chapter 6.

6 Reflections and discussion

6.1 Introduction

This chapter presents a discussion of the research findings in relation to the research objectives (Section 1.5), from which a clear identification is presented of how the findings have contributed to new and developing knowledge in the use of BNs for decision support.

6.2 Suitability of BNs for decision support in WRM

6.2.1 Use of BNs to inform WRM

In Chapter 2, the use of BNs were reviewed to address RQ 1.1 and were identified to be an emerging and useful technique to inform the management of water resources. The contextual applications, and the methodological approaches to the use of BNs were investigated and are compared to the findings from the current research.

Throughout the reviewed literature, BNs were demonstrated to be beneficial for the development of strategies by government agencies for the management of water resources at a river basin and catchment level. These were predominantly focused on water quantity management, with a few limited applications to quality management (e.g. phosphorous and pesticides). Initial demonstrations of the use of BNs to inform WTW operations have also been conducted, although these have been limited to only three studies involving process optimisation and treatment process selection. The implications of the WFD for the management of water resources was also analysed through the use of BNs, both to assess specific WFD measures to be used (e.g. management practices to reduce phosphate in SW [Barton *et al*., 2008]), and to support integrated and participatory decision making (e.g. Henriksen *et al.*, 2004; Zorrilla *et al*., 2007). The research conducted and presented in this thesis involved the use of BNs in assessing the implications of the WFD PoMs (e.g. designations of DrWPA, Water Protection Zones, and Safeguard Zones; as well as the 'effectiveness' of such measures) on the raw water quality, in addition to the implications for WTW at a specific site (e.g. ion exchange requirements). BNs were also used to incorporate water company specific measures to influence the management of the catchment. In the development of BNs, and the Hybrid-DSP, the ethos of the WFD was adopted through the integration of multiple aspects of water management, alongside the encouragement of a participatory approach to decision making. Therefore the resultant Hybrid-DSP offered a new approach to incorporating the implication of the PoMs implementation on investment decision options considered by the case study company.

The use of BNs has been found within the literature to be appropriate for both participatory (workshops, meetings, interviews [e.g. Henriksen *et al*., 2004]) and non-participatory (technical development [e.g. Ghabayen, 2004]) applications. When BNs were used in a participatory approach, they were used to engage stakeholders in decision making (e.g. farmers, water company representatives, NGOs [Henriksen *et al.*, 2004]), and develop an understanding and awareness of the problem domain. Within this research the researcher undertook the technical development of BNs (e.g. through linking diverse variables over time), supported by consultation and collaboration with the reference group members (e.g. to establish the impact of the WFD on the management of GW quality and on treatment requirements). The technical developments in the demonstration of the BNs for the problem domain of GW nitrate contamination, over both five and six year temporal cycles represented a new contribution to knowledge, although developed based on the knowledge elicited from the managers through the reference group, the fully developed model would require further verification from water managers to confirm its representation of the problem domain. The incorporation of a participatory approach was limited to representatives of the reference group, which although contributed to organisational learning, would require wider application to increase engagement and further develop organisational understanding of the problem domain.

BNs have previously been applied to water quantity and quality aspects as well as to groundwater and surface water management. In the specific context of groundwater quality, one study has considered the impact of pesticides (Henriksen *et al.*, 2004). However, the specific case of nitrate contamination in groundwater had not been reported within the BN literature before. In this study the use of BNs is explicitly used to address the problem. The difficulties associated with understanding the movement and residence time of nitrate in groundwater presented a specific problem, and BNs were able to offer a mechanism to represent the integrated nature of the problem. This represented a first attempt to understand and represent the predicted GW nitrate concentration as a result of the impact of the WFD PoMs implementation over time. This therefore offered a new process, which the water company could use to predict nitrate concentrations using the best knowledge available, to inform future investment requirements for potable water treatment.

The use of dynamic (DBNs) and object orientated (OOBNs) BNs, have recently proven to be a developing area of research (e.g. for decisions which include multiple farming types, and aquifer units; [Carmona *et al*., 2011]), although issues related to the use of BNs for contexts which exhibit such increased complexities have been recognised (e.g. Barton *et al*., 2005). Within this research a range of BNs were developed including simple and more advanced dynamic networks. The use of a dynamic BN structure, as previously mentioned, was selected to represent the temporal regulatory periods of the problem domain, being the five yearly AMP cycle, as well as the six yearly RBMP cycle. This representation of the multiple cycles within a BN, related to the UK water sector, is the first representation of its kind.

BNs were previously recognised to be coupled with other techniques to enhance decision support (e.g. DPSIR framework [Barton *et al*., 2008; Langmead *et al*., 2009]; evolutionary multi-objective optimisation [EMO] [Farmani *et al*., 2009]; ecological risk assessment [ERA] [Chan *et al*, 2010]; agro-economic models [Carmona *et al*., 2011b]). Couplings with existing deterministic models have been used to enhance the credibility of BNs through the provision of more deterministic, as opposed to subjective, data to populate the BNs (e.g. Holzkämper *et al*., 2012). However, within the literature, coupling of BNs with problem structuring or problem domain characterisation techniques has not been widely reported. This is despite the recognition of the need to have well defined variables within the problem domain prior to the construction of a BN (Kjaerulff and Madsen, 2008). Within this research, the use of BNs was enhanced through the coupling of problem domain characterisation techniques prior to the development of the BNs. This coupling was instigated in response to initial findings from the use of BNs that indicated difficulties in specifying variables and states within the problem domain. Therefore the use of categories (e.g. PESTEL, DPSIR) to both identify variables and to characterise known variables provided a means to understand the problem domain, whilst also incorporating stakeholder analysis to understand the influential stakeholders affecting the implementation of specific WFD measures. Through the use of these techniques a greater understanding of the nature of the variables to be used within the BNs was generated. This enabled a thorough understanding of the problem domain, whilst also informing the probabilities incorporated within the BNs. Hence, the coupling of the techniques, offers a new enhanced participatory and integrated process which could be applied to problem domains which are less well defined, and are subject to many uncertain, complex and dynamic developments. The importance of understanding the whole system within which decisions are to be made is now recognised to be of paramount importance. Therefore this combined approach through the BN based Hybrid-DSP, offers a step towards more integrated and holistic decision making within the water industry.

6.2.2 Organisational perspectives of BNs

Within the reported literature in Chapter 2, there have been very limited studies reporting the perspectives of organisations on the use of BNs. The perspectives elicited from the previous studies indicated that organisations favoured the technique as it allowed water managers to understand the cause-effect relationships between multiple diverse variables within the problem domain. This was based on its visual representation of the problem domain which enhanced communication with stakeholders, whilst also providing a platform for informing and promoting integrated and participatory decision making (Henriksen and Barlebo, 2008). However, the perceived limitations were acknowledged to be related to the time and resources available, as well as the level of knowledge of the water managers regarding the use of the BN technique (Ticehurst and Pollino, 2010). The use of an independent facilitator to manage the process of participatory development of BNs was also recognised as a prerequisite for further BN use (Henriksen *et al.*, 2007c). The perspectives from end-users within the research undertaken in the current study were also investigated in response to RQ 1.2, which indicated BNs were a useful approach and assisted in the development of a more holistic perspective of the influences and inter-relationships of variables affecting the decisions regarding the management of potable water supplies. However, the use of BNs also had some challenges for end-users within the study. These included the difficulty in understanding the BN methodology by users who were not familiar with probabilistic modelling techniques. This was apparent during the reference group and focus group meetings, as well as during interviews with informants. Other constraints on the use of BNs within the research included the limited time available by the water managers (mostly due to the demands of their day job), rapid developments in the water sector during the time period of the research (hence multiple changes to the BNs developed) and the amount of data required which may (or may not) be present or available. In addition concerns over the suitability of BNs for use across multiple sites, where individual BNs would need to be developed for >100 WTW and associated catchments could present logistical implementation problems. These findings further complement those found in the literature by Ticehurst and Pollino (2010) and Henriksen and Barlebo (2008), whilst also increasing knowledge regarding the practicalities of their use specifically within a water company for multiple sites.

6.3 Organisational decision processes and the WFD

In order to address Research Objective 2, and hence RQ 2.1 and 2.2, an assessment of the case study organisational processes was undertaken to establish the extent of the inclusion of WFD implications for potable water management within the existing decision processes and systems. This assessment was presented in Chapter 4, which indicated the limited ability for existing systems (CRAGS, DWSP, Risk and Value, Asset Plus+, FORWARD) to assess the implications of the WFD. The assessment highlighted that as the WFD implications were not clearly defined during the time of the conduct of the research, the organisation adopted the use of an internal working group (the WFD Working Group) to process and disseminate the incremental developments of the WFD. The implications for investments were also identified through this group, which were supported through other liaison groups with the EA. This review highlighted that no structured appraisal of the impact of the WFD was in place, with no system to address the “holistic” issues regarding the management of water resources being brought about through the WFD. Instead multiple issues were being addressed in an incremental way, responding to the requirements of the environmental regulator: the Environment Agency. This evidence of a limited system in place by a water company and the absence of a process within the water sector to respond to the new holistic approach advocated by the WFD therefore presented an opportunity to develop a new Hybrid-DSP. A proposed BN based Hybrid-DSP has been developed through the research undertaken and presented in Chapters 4 and 5. The proposed process is developed using criteria established from the organisation, and the utilisation of existing techniques within the disciplines of strategic management. This process, therefore contributes a new process to the water industry to address the uncertainties and complexities facing the management of water resources for potable water supply. Further discussion on its development and application is presented in the subsequent sections.

6.4 Development of a Hybrid-DSP to explore organisational implications of the WFD for potable water supply

In answering Research Objective 3, Research Questions 3.1 – 3.4 were addressed. The discussion of the findings from addressing RQ 3.1-3.4 are presented in the following sections.

6.4.1 Design criteria and selection of techniques and methods for decision support

The criteria established for the development of the Hybrid-DSP (as discussed in Section 4.4) in answering RQ 3.1 and RQ 3.2, although informed from the case study organisation (from observations, interviews and discussions in reference group meetings), were also guided by the WFD and decision support literature. The dynamic nature of the research environment, had a direct influence on the criteria established which required an iterative review of the design of the Hybrid-DSP. The criteria were established for the approach to the use of the Hybrid-DSP, its performance and its ability to integrate with the organisation. However, in taking this approach, the techniques applied through the design of the Hybrid-DSP were able to facilitate and respond to the iterative changes in the research environment. Specifically the design of the BN itself, was able to be adjusted to accommodate the specific output variable which could be incorporated within the case study organisations' investment planning system, Asset Plus+. Although, ideally establishing the criteria for a new Hybrid-DSP at the start of a project would provide definite guidelines for a decision support process, in reality the substantial changes within the research context directly influenced the design of the Hybrid-DSP. Hence the emergent use of the selected techniques during the unsettled, complicated and dynamic research environment further supported a flexible and holistic approach to the design of the Hybrid-DSP.

BNs as a tool was selected, due to the contemporary debate over its usefulness in supporting strategic policy making in relation to water resource management, as discussed in Chapter 2. Many existing techniques are not necessarily able to incorporate an holistic approach to the management of water resources, whilst also incorporating an integrated and participatory approach. In addition the promotion of these features of decision making by the WFD, support the selection of BNs for use within a water company, to facilitate the development of a strategic alignment between decisions being made regarding water resources in the external environment, and those being made within the organisation. Hence, this alignment would offer increased effectiveness in decision making, and communication between decision makers from within the organisation and the external stakeholders (e.g. industry regulators, businesses, customers).

Additional techniques were also selected to enhance the use of BNs, and provide a more holistic decision support process to understand the implications of the WFD on potable water management. These techniques included the selection and adaption of strategic management frameworks (PESTEL, SWOT, resource and capability assessment), whilst also including stakeholder analysis and a causal analysis framework (DPSIR). The use of the strategic management techniques in association with BNs had not been recognised before in the literature reviewed. Therefore the adaptation and coupling of these techniques enhances the use of BNs for strategic management applications. This is further discussed in Section 6.4.2 and 6.4.4.

6.4.2 Approach to the application of the techniques and methods

In answering RQ 3.3, an exploration into the way in which the selected methods could be used was conducted through the trial applications and development of the selected techniques. These iterative developments, resulted in an overall approach to the use of the methods and techniques in a combined approach as part of the BN based Hybrid-DSP.

The approach taken for the development of the BNs and overall Hybrid-DSP was one which incorporated participation by the stakeholders within the case study organisation. Using a participatory approach to the design of decision support, and the use of BNs has been identified previously in the literature (e.g. Zorrilla *et al*., 2010) to be a beneficial approach, fostering a greater sense of ownership and involvement of the end-users in the process developed. Within the research, the participatory approach used resulted in the development of a broader understanding within the organisation of the problem domain, and in the use of the specific techniques. In developing the Hybrid-DSP a range of organisational perspectives were obtained through informant discussions, presentations to the WFD WG and through a central reference group. Although there were only five consistent members of the reference group, they were representative of the main departments who would be engaged in the overall implementation of the Hybrid-DSP, and therefore were able to challenge the development of the Hybrid-DSP from different perspectives. This assisted in guarding against the potential disadvantage of using a small group as recognised by Cain *et al*. (2003), being the limited ideas or offerings of different perspectives. Another problem, they recognised in the use of small groups was the potential convergence of perspectives over time. Within the research to guard against this, the members were encouraged to share information in relation to contemporary organisational and regulatory developments (e.g. contamination events in potable water supplies, regulatory developments and political perspectives of Ofwat, DWI and the EA in relation to the WFD implementation). This, therefore enabled the members to challenge the relevancy and usefulness of the developing Hybrid-DSP over time in relation to the changes in the strategic and operational environment (e.g. the incorporation of aspects of the DWSP, the inclusion of a cost and benefit assessment or not depending on the Asset Plus+ system being designed, inclusion of the emerging AWS catchment management interventions).

During the development of BNs and the Hybrid-DSP, the researcher took on the role of facilitator as well as an informant (to inform the organisation of WFD issues, and introduce the techniques used within the Hybrid-DSP). This was challenging, through future applications of the Hybrid-DSP and development of BNs, the use of an independent facilitator would be recommended to reduce any potential bias, whilst also encouraging active participation of group members. This had also been recognised previously in the development of BNs, which had benefitted from an independent facilitator (not the researcher) (e.g. Cain *et al*., 1999; Henriksen *et al*., 2004).

Even through sustained and repeated meetings and one to one sessions with key informants and reference group members were undertaken through this research, a full understanding by water managers was not necessarily achieved for the development of BNs. Therefore although it was the aim to adopt a participatory approach, it became apparent that the engagement with the company would be focused on; understanding the company, the requirements and obtaining data for use within the model development. This information collected during the research, was continually presented back to the reference group for feedback and to stimulate discussion to support holistic learning of the wider issues affecting the management of water resources. The challenges of maintaining a participatory approach through the development of the BNs resulting from this study, confirms the experiences of other attempts to work alongside an organisation in the development of BNs (e.g. Ticehurst and Pollino, 2007 & 2010). This study, therefore highlights the benefits of using BNs, although also recognises the transfer of knowledge and understanding to decision makers can be challenging.

The approach adopted for the use of the stakeholder analysis, was via a facilitated exercise within Reference Group meeting No.5, to promote organisational understanding of the level of interest and influence of different stakeholders. This was a particularly useful exercise in establishing an open debate regarding the different stakeholders managers identified, and how the managers perceived the level of interest and influence of each of the identified stakeholders in relation to the management of nitrate in groundwater. As a technique, its inclusion within the Hybrid-DSP promoted organisational awareness and informed the basis of the likelihood of relevant stakeholders (attributed to specific variables included in the BN) to implement any proposed PoMs, and hence the potential effect on water quality.

6.4.3 Construction of BNs

During the research, the level of understanding of the dynamic problem domain by the managers, and the lack of sources of data to substantiate the links presented difficulties in the construction of the network structure, and the development of the CPTs using participation. This was evidenced through engagement with the organisation during reference group meetings, and the individual one to one meetings held between the researcher and the key informants in the organisation. These difficulties were also experienced by Henriksen *et al*. (2007) during the development of BNs for the management of groundwater quality. In addition, Cain *et al.* (1999) had also recognised that engagement of non-specialist stakeholders in the development of Bayesian networks would not be easy, as a result of the participants unfamiliarity with the technique and the potential complexity of the problem domain.

The use of BNs as part of the Hybrid-DSP promoted an approach which could be updated as new information becomes available, and therefore the output from their use can be updated to refine decisions made regarding the management of potable water at specific sites. Cain *et al*. (1999) also identify that the outcome of a BN and the decisions taken with regard to the information and perceptions used to develop the BN, should not be considered to be binding, and should be updated as the physical environment changes and the perceptions of the stakeholders change over time. Therefore monitoring and evaluation of the changes which may affect the decision environment need to be conducted effectively to ensure the decisions are still relevant for the decision space.

One to one development of the BNs was not possible during the research. This was due to a restricted number of ‘independent` computers which the BN software was licenced to be loaded onto, as well as the time required by managers to be involved in building the BNs. In order to encourage participation in the development of BNs, both the legal and technological constraints, together with the allocation of available time of managers or team members, should be assessed prior to implementation of the technique. Where these issues are not addressed, the sustainability of the use of BNs could be questionable, resulting in restricted development of internal resources and capability for continued implementation. The highlighted issues of time and resource availability also confirm the findings by Henriksen *et al*. (2008), and Ticehurst and Pollino (2010). However the limitations of the use of BN software within a company has not previously been reported as a constraining issue, which may reflect the focus of previous government or academic led research, as opposed to practical use within an operational environment. Another specific problem related to the practical application of BNs, concerned the managers, who did not consider themselves to be the people who would be developing the BNs. This reluctance to be involved in the details of BN development limited the extent of the participatory approach, used in joint meetings and focus groups, with the emphasis on the researcher developing the networks for presentation, discussion and review, within the reference and focus group meetings.

The CPTs were informed by the data collected by the researcher (observations, notes, literature, information from meetings, interviews, workshops held). Although these data sources offered a basis upon which the network could be developed, complete validation of the CPTs was not achieved with the water managers. Therefore the CPTs used present the subjective view of the researcher based on the collected evidence only. These would need to be further verified by the water managers to ensure the results were representative of the problem domain modelled, as recommended by Henriksen *et al. (*2007c) and Martin de Santa Olalla *et al*. (2007). The difficulty in establishing conditional probability tables for groundwater is recognised by Al-Chalabi and Shihab

(2008), where they further propose that methods should be developed to make it easier to select and justify the CPT values used.

The development of a BN structure which is dynamic represents a contribution to knowledge, as a new application of BNs to model the management of water across multiple time steps. In this research, both the time steps of the RBMP six yearly cycles and the AMP five yearly cycles were incorporated. Most applications of BNs have only considered a static representation of the decision problem over a limited time frame (e.g. one year Henriksen *et al*., 2008), to investigate the causal relationships between management actions and impacts on variables. This limited assessment of the impact of management actions over time, is a constraint in the long-term assessment of management actions. Only in recent years has the incorporation of dynamic time steps been presented for WRM (e.g. Carmona *et al*., 2011), and hence further calls for more research into the use of dynamic BN applications has been made (Barton *et al*., 2012). Although validation of the use of DBNs are recognised to be difficult, as no data exists for future events (Barton *et al*., 2008).

During the development of BNs as part of this research, only one aquifer unit was considered, however this could be extended to look into multiple aquifer units or boreholes as part of one holistic BN. This has very recently been explored in one of the first applications of the use of object orientated Bayesian networks (OOBNs) in the field of WRM (Carmona *et al*., 2011a), and therefore indicates this is an active area of contemporary research.

6.4.4 BNs coupled with other techniques

In the design of the Hybrid-DSP, as a result of the initial findings using BNs, further strategic management techniques were coupled with BNs. The way in which these additional techniques are used further contribute to answering RQ 3.2 and RQ 3.3.

In the development of BNs, the initial stage is to define the variables. During this research the definition of variables was a time consuming process. This was due to the limited understanding by the researcher and managers within the organisation of the WFD implications for the management of water treatment. As the implementation of the WFD progressed with further clarity on the management interventions within specific catchments, these variables were incorporated in the Hybrid-DSP. The use of the DPSIR and PESTEL framework specifically supported the identification of the variables which would impact on the management of water resources within a specific catchment. In coupling techniques with BNs, there are limited studies incorporating the use of DPSIR as a framework to inform the design of a BN (Barton *et al*., 2008). Although this proved to be useful, further exploration on their use in conjunction with BNs is required. This research therefore positively contributes to this discussion, by offering further insight into the potential of combining the DPSIR framework within a Hybrid-DSP, to inform the variables and structure of a BN.

The development of the Hybrid-DSP applies both conceptual network coupling where techniques are used to structure the problem domain (PESTEL, DPSIR), as well as integrating the output from the BNs, to inform organisational strategy development (into the Asset Plus+ system). Therefore this research complements the recent developments by Kumar *et al*. (2010) in the development of 'soft' coupling approaches with BNs.

The use of BNs in combination with stakeholder analysis, has not been presented before within the literature, although its use alongside the development of a BN has been regarded by water managers to be beneficial within the research. This has been in relation to the development of an understanding of the sphere of influence stakeholders have in the management of water resources. Although not necessarily directly coupled with BNs, their use is supported to further inform organisational understanding of the role of stakeholders and their responsibility in the management of water within the wider catchment. This is now an increasingly important issue, resulting from the implementation of the WFD and the associated drive by the UK Environmental Agency in "Working Together" to sustainably manage water resources.

As previously identified, the Hybrid-DSP developed contained a substantial problem structuring stage to generate a more integrated understanding of the problem domain prior to the development of BNs. This was recognised by the researcher to be an important component in the targeted development of BNs to understand in detail the implications of the WFD for a specific site. However, the use of the proposed detailed analysis of the problem domain could be time consuming and resource intensive, and therefore not practical for application. Therefore further development of possible structural learning algorithms for application (e.g. Alameddine *et al.*, 2011) could be investigated, although would only be applicable once datasets become available (e.g. through the monitoring programmes from the EA as part of the RBMP PoMs).

Within the literature BNs are not applied in a consistent manner (see Chapter 2), and therefore there are many alternative ways to understand a problem domain; collect the data (through participatory or none participatory methods); develop both the structure and the conditional dependence relationships within a BN; and analyse the results of the BN and deem whether they are suitable for a given situation. In this research discussions and reference groups were used to promote participation, however, the researcher recognises that other approaches advocated within the literature to promote both a participatory and integrated learning approach could also be used. These include cognitive mapping or flow diagrams to understand the causal relationships within the problem domain, as well as pre-formatted matrices to establish prior probabilities, conditional probability values and posterior values from experts within the organisation. Therefore although the combination of the proposed frameworks within the Hybrid-DSP are recognised, further exploration of additional or supplementary techniques could be undertaken, depending on the circumstances and level of understanding of the problem domain by managers.

The BN based Hybrid-DSP presents a new holistic approach to the systematic identification and structuring of variables for inclusion in detailed modelling using BNs to inform strategic organisational responses to ensure alignment with WFD objectives and strategic organisational goals. The approach is systematic and versatile which could be used for complex decision problem domains, in either an expert review panel or through further interactive learning opportunities. The basis of the model is a Microsoft Excel 2010® spreadsheet, which could be maintained and developed within the organisation as it is a familiar interface with personnel in the organisation. No other Hybrid-DSP has been reported in the academic literature which combines the proposed techniques to be used collectively to inform the strategic management of water resources. Therefore this process is offered as a contribution to knowledge and as a technique for further application within the water industry.

6.4.5 Implementation and integration of the Hybrid-DSP

In answering RQ 3.4, the integration of the methods to form the Hybrid-DSP was conducted, along with the implementation of the process within the case study organisation.

As Varis and Kuikka (1999) acknowledged, it is not enough to merely learn and apply a methodology, but it needs to be comprehended and accepted by others even when their interest may not be in the development of the approach, and furthermore to be introduced and accepted into organisations. Through this research this has been achieved to an extent, where the methodology has been introduced to the water company and has been developed and worked on through three consecutive years.

In conducting the research, the researcher was able to provide a consistent approach to the use of BNs and the techniques within the Hybrid-DSP. However for implementation within the company, instead of the researcher, a system modeller would be required with the knowledge to implement the techniques consistently. The role of a system modeller in the implementation of such a process incorporating BNs, was also acknowledged to be required by Kumar *et al.* (2008), Holzkämper *et al.* (2010) and Lerner *et al.* (2012), through their application of the MEM process incorporating BNs for Integrated Catchment Management.

Initial problem structuring to understand the problem domain would allow for the sharing of knowledge regarding the specific sites of interest, whilst the second phase would allow for more detailed analysis of the specific conditions and management measures implemented for a specific site. The ability to update the success of the management measures applied as data became available (e.g. success of DrWPAs, WPZs, Safeguard Zones, NVZs, AWS workshops for awareness raising with stakeholders) would also be able to be achieved, and therefore provide for adaptive management approaches to be taken by the water company, towards the management of water resources. Combinations of management interventions could also be explored within the BNs to identify the optimum combination to be implemented (e.g. AWS measures, and PoMs).

Through the predictive capabilities within BNs and the representation of uncertainty across the variables, knowledge gaps can be identified to help to target further resources to understand relationships between variables within the model of the problem domain. To achieve this, further use of Value of Information (VoI) analysis within the BNs would allow for the identification of where more resources are required in order to reduce the uncertainty surrounding the nature of the relationships between variables within the network. This is supported by Barton *et al.* (2012), where the use of prior knowledge is advocated, followed by a systematic analysis of the Value of Information for each of the causal relationships, to improve understanding and targeting of resources. However, they also recognise the potential weakness in this approach where VoI can only be applied to existing causal relationships within the model, therefore not allowing for the investigation or development of new relationships for other causal connections.

Recent changes within the organisation to promote increased understanding and management of risks at the catchment level, prior to determining treatment interventions were observed (e.g. the drinking water safety planning approach). This risk based approach at the catchment level will aid the acceptability and implementation of the proposed Hybrid-DSP, although implementation issues such as resistance to change; degree of support from top management; and user training, as highlighted by Turban *et al.* (2007) may still present operational challenges.

The Hybrid-DSP approach is transferable to other problem domain contexts, which could be considered for the management of the water supply systems beyond the case study region, and potentially beyond the UK. This generalisation is founded on the principles upon which the Hybrid-DSP was developed which incorporated management science, organisational theory, decision analysis, and environmental modelling. The incorporation of available knowledge using qualitative problem structuring methods followed by the use of BNs as a quantitative analysis presents an integrated approach which could be utilised in other problem domains exhibiting complex and integrated issues (e.g. natural resources management).

Integration of the BN based Hybrid DSP was successfully achieved within the case study company during this research. Integration with the Risk and Value process, DWSP and Asset Plus+ were identified as options, although the focus was on the updating of the Asset Plus+ risk profiles of asset performance. This aimed to inform the likelihood of service measure failures used to determined investment requirements. Therefore the approach was recognised as a tool to be used flexibly to inform investment requirements on an annual, or event driven basis, for specific sites. Multiple departments were identified to be involved in the process, to ensure representation from the different perspectives of the business are included, and hence to promote organisational learning through the use of the process. In the current climate of holistic and integrated decision making, this is recognised to be a suitable approach to promote engagement and awareness raising across the organisation.

Within this research the Hybrid-DSP provides a strategic and tactical decision support tool, which has been illustrated within the UK water industry. The use of BNs as a central modelling tool, allows for the combination of the strategic elements within the problem domain, and hence facilitate the analysis of management intervention options to be considered by an organisation. Consequently these can be linked into the formulation of the strategic organisational business plans, to contribute towards more sustainable management of water resources.

6.5 Discussion of the results of the Hybrid-DSP demonstration

In the design of the Hybrid-DSP through addressing Research Questions 3.1 – 3.4 a full demonstration of the process was presented in Chapter 5. The Hybrid-DSP incorporated the use of a spreadsheet to centrally manage the data used during the process, and hence, facilitated a transparent record of the information and data sources used to inform strategic options for consideration. The results obtained from the demonstration are discussed in the subsequent sections.

6.5.1 Phase 1 results

Through the generic assessment conducted within Phase 1, the identification and characterisation of the impacts on the management of potable water was achieved through the structured approach as outlined in Section 5.3.1 through Steps 1.1-1.8. This included an assessment of the nature of the factors in relation to the PESTEL categories, the location within the potable water supply chain which they may affect, the specific water body which they may target, and the associated stakeholders. A quantitative summary of the factors' characteristics were presented in Section 5.3.1, which highlighted the dominant types of factors (e.g. environmental and legal) and those which present less of a concern (e.g. social factors). Of interest is the difference between the WFD factors, and those which are classed as general factors. The emphasis of the WFD related factors on the management of potable water supplies indicated a definite focus on the legislative and environmental factors, with more attention at the management level of potable water, as opposed to the specific treatment aspects related to potable water. In addition to the characteristics of the factors', the relevant stakeholders were also identified. This highlighted which stakeholders are more frequently associated with the factors. Hence, further engagement with significant stakeholders could be identified, these being the EA, farmers, and other water companies. In addition the prioritisation of stakeholders to engage with, through the subsequent stakeholder analysis (in Phase 2) provided a further assessment of the influential and interested stakeholders, with whom potential strategic relationships could be developed. (The analysis of stakeholders could also be conducted within Phase 1, although this was carried out specifically within the demonstration of the Hybrid-

DSP). The specific qualitative details are captured within a large matrix within the supporting Microsoft Excel 2010 ® spreadsheet used to manage the data during the demonstration of the Hybrid-DSP (exerts of which are presented in Appendix F). Through conducting this holistic and structured assessment of the influential factors, the water manager is able to develop a broader understanding of the influential factors affecting potable water supply. Understanding the nature of the factors affecting potable water supply, had previously been conducted using ‘tacit knowledge’ or in part by different representatives of the business for specific purposes. Using this systematic approach offers greater consistency in the elicitation and characterisation of factors for further analysis to inform potential potable water supply strategies. Through using this characterisation process, a central database of the influential factors and how they affect the potable water supply is generated, which can be drawn upon for further analysis at both the general level and for specific sites (e.g. through Phase 2). No existing models or decision processes within the company had previously involved characterisation of factors in this way, and therefore this process offers a new systematic process to identify significant factors having a strategic or operational influence on the management of the potable water supply chain.

The assessment of the organisations strengths and weaknesses, against the potential opportunities and threats posed by the factors identified, further allowed for the identification of areas for the development of resources and capability within the organisation. In undertaking this assessment, it became clear that investment options should be focused on developing skills within the organisation, promoting communication and collaboration, as well as further investments in technologies and changes in the cultural environment. Undertaking this analysis of the types of organisational responses would allow managers to think more broadly about the type of organisational responses to a perceived problem, which historically would have had a tendency for a ‘technological solution’ as opposed to more ‘social or cultural’ solutions. (This was evidenced during the initial stages of this research, where technological solutions were the focus of the inquiry, although as developments in the problem domain took place, and understanding of the WFD implications improved, a recognition of alternative investments was established). During the research the significant shift in focus towards more holistic planning was evident and presented a real challenge for the reference group to understand and manage. The resistance to change was in part a condition of the strong cultural traditions within the UK water industry, as well as the systems and processes established within the water company.

The assessment of resources and capabilities identified some common organisational investment responses, which were presented in Table 5.7. The assessment of the strategic importance and relative strength of the organisation to deliver these responses further informed potential strategic options for consideration at both a general and/ or a site specific level. Therefore through the conduct of the assessment as part of Phase 1 of the Hybrid-DSP, water managers would be able to establish general organisational responses to specific changes (e.g. such as the WFD implementation) within the strategic business environment. A strategic screening process had not been identified within the water company prior to the development of the Hybrid-DSP, and therefore this initial characterisation of the problem domain and identification of general organisational responses offers an holistic analytical approach to raise awareness and understanding amongst water managers. Through a more detailed understanding of the problem domain, a more focused approach to the development of further BNs for site specific detailed analysis could be conducted.

The process of categorising factors and thinking through how the factors impact on the potable water supply chain, could be labour intensive. However, if conducted through a facilitated workshop environment, the discussions held within the open forum would contribute to the generation of organisational knowledge through active discussion of the factors. In addition the representation of a cross-section of business units within the facilitated session would provide for a greater ‘cross-fertilisation’ of ideas and provide a wider understanding of the problem domain being assessed. Using a similar approach to conduct the SWOT analysis and the identification of potential organisational ‘responses’ would also contribute to the generation of strategic investment priorities as perceived from multiple perspectives. Through the utilisation of wider business representation in the conduct of the Hybrid-DSP, especially during Phase 1, increased organisational learning and awareness of strategic issues affecting the business would be achieved.

6.5.2 Phase 2 results

During Phase 2 the analysis was focused on a specific site (Barrow WTW and the local catchment). Of interest was the specific 'pressure' of nitrate application within the local catchment, and its impact on GW nitrate concentration. The initial characterisation process as conducted for Phase 1 allowed for the identification of additional site specific and pressure specific factors to be identified and assessed. The prioritisation of these site specific factors alongside the existing factors identified in Phase 1, therefore provides for a comprehensive identification of factors to be further assessed in more detail. The purpose of more detailed assessment is to focus on establishing with greater certainty how changes in the external environmental (e.g. WFD implementation) will affect the management of potable water supplies for a specific site and hence inform investment requirements.

In undertaking the Phase 2 analysis, a detailed stakeholder analysis was carried out, to specifically identify the stakeholders and their level of influence and impact at the specific site. This analysis was conducted by water managers, and hence it represents the perceived level of interest and influence of the stakeholders identified. This analysis offers an opportunity to identify any stakeholders related to a specific site which may justify the development of specific strategic relationships or partnerships to address the problem of nitrate in groundwater. Through the assessment conducted several stakeholders were identified for the Barrow site, which were classified as supportive, neutral and negative in relation to the problem of nitrate contamination in GW. This more detailed assessment provided for a greater depth of understanding by water managers of the interest stakeholders may have in addressing nitrate contamination. The potential stakeholders which AWS could develop partnerships with were also discussed as a result of the stakeholder analysis. Once again, undertaking this analysis in a facilitated forum further develops organisational awareness of the sensitive relationships between both AWS and the identified stakeholders, as well as potential sensitivities or collaborative relationships between the stakeholders themselves. During a period of increased focus on integrated decision making, conducting stakeholder analysis for site specific or issue specific problems will become of greater importance. Water companies can no longer focus on the management of their asset base in isolation from the strategic changes facing the industry. Rather a greater integration and awareness of the changes in the surrounding strategic landscape need to become part of a business as usual approach.

Through the causal analysis conducted using the qualitative DPSIR framework as a template to inform the latter more quantitative BN analysis, a greater awareness of the integrated landscape between the identified factors is generated. Although the DPSIR approach can provide a framework as a basis for discussion, the terminology was recognised by water managers to be confusing. However, using the DPSIR approach would facilitate alignment of the water company with the processes used within the EEA for the assessment of the environment, as well as aligning with the WFD implementation, which use the DPSIR approach to inform the PoMs. The combination of the DPSIR with the BNs has been reported in the literature although only in a limited number of articles (e.g. Barton *et al*., 2008; Langmead *et al*., 2009), and therefore the further development of its use in combination with the Hybrid-DSP represents a further contribution to knowledge. The use of the DPSIR within the research enabled a greater understanding of how the existing measures used from current legislation address the state of the nitrate in the groundwater, whilst also identifying where limited measures were in place to address specific D-P-S or I elements of the causal chain. Therefore through the use of the DPSIR, any additional ‘organisational responses’ could be identified, and added to the main list of factors (now to become variables) within the BN for further detailed analysis.

The subsequent analysis using BNs provided a detailed assessment of the impact of WFD measures over both the six year review cycles of the RBMPs, as well as the five year review cycles of the AMPs. Therefore in devising a BN to cover multiple time periods, an assessment of the likely impact of the WFD measures over time for the specific site could be assessed. In addition the impact on raw water quality for the site would be able to be reviewed in line with the five year AMP cycles. However, the proposed dynamic BN has limitations. The development of the CPTs were mostly through the subjective opinion of the researcher, using evidence to inform the probabilities where available. Ideally further consultation with the water managers to establish these CPTs would be beneficial to ensure they understood and informed the BN more directly. This would be a further step to review the final BN for Barrow with the water managers. In addition identifying which variables to include or remove was challenging. Maintaining a parsimonious network to minimise the variables has resulted in the simplification of the complex ‘real world’ situation at the site. In fact further boreholes are associated with the Barrow WTW, which ideally would need to have detailed BNs developed for each of the boreholes separately. Although this was regarded by the researcher to be too complex to be incorporated into the dynamic model, and therefore assumptions were made regarding the availability and quality of the additional water used to ‘blend’ with the water abstracted at Barrow for supply.

The inclusion of measures of NVZ, DrWPA, WPZs, and Safe guard zones represented all the legislative measures available to control nitrate in groundwater. Although the effectiveness of these measures has not been recorded directly, and in the case of WPZs, DrWPA and safe guard zones, these were not implemented whilst the BNs were being constructed. Therefore data regarding the effectiveness of these measures was non-existent. The use of subjective probabilities in these cases can therefore be used, although this provides some indication of the likely impact, no actual values can be attributed until after the measures have been implemented and monitored.

Through the conduct of scenario analysis using BNs, alternative management options as well as assumed levels of effectiveness of the WFD measures were able to be assessed. The output from this assessment is concerned with the targeted variables of raw water quality and hence the implications for further treatment requirements into the future for Barrow WTW. In the scenarios conducted, the existing high levels of nitrate in the raw water and the increasing trend of nitrate contamination has resulted in continued treatment requirements at the site into 2030, despite the best case of all the WFD measures being successful.

In this demonstration a Value of Information analysis was conducted to establish where further investment could be targeted to reduce the uncertainty within the network. Using this function within the BN software provides a more detailed analysis of the BN to identify where more investment to reduce the uncertainties associated with the variables could be made. In using this assessment further response options could be identified, or the gap in knowledge could be related to an existing proposed organisational response.

Following on from this, the qualitative assessment of the options presented from the detailed analysis in Phase 2 using BNs, as well as the generic analysis of response options from Phase 1, was conducted to align the proposed options with the organisational strategic objectives. This allowed for the proposed investment options to be understood in relation to the overarching strategic objectives of the organisation, and hence promote further integrated and holistic decision making regarding more sustainable and long-term investments.

Details of the demonstrated BN

In a dynamic BN the temporal assumptions are not the same for every site, and therefore would need to be altered. In the case of Barrow, as it is a shallow aquifer, and high susceptibility to contamination, the time period was assumed to be five years for movement of contaminant into groundwater. Therefore at other sites, the impact would be different dependent on the factors affecting the susceptibility of the site to contamination. On this basis, a range of categories for an assumed ‘time to impact’ could be developed, where although detailed modelling of the transmission of contamination into the aquifer could reveal site specific or geological time period, the high level of uncertainty, could be better represented through the grouping of certain physical conditions for each groundwater site. The grouping of these physical conditions could be further related to a set of assumptions regarding the ‘time to impact’ for the site. These assumptions could therefore be used, to allow for the construction of a range of Bayesian networks, which could be used as ‘standard’ ‘time to impact’ scenarios, which could be applied to the various types of borehole susceptibility conditions. This was not conducted within this research, although it would be an opportunity for further development, and would support recent developments in the use of OOBNs promoted by Carmona *et al.* (2011a) and Carmona *et al*. (2011b).

The case study site used for the development and application of the Hybrid-DSP was an extreme site with a known history of high levels of nitrate contamination. Therefore further testing of the use of the Hybrid-DSP for a marginal site, which is not heavily contaminated, instead with the nitrate concentration below 45 mg/l but with a rising trend (hence failing the WFD objectives), would present an alternative scenario. This would allow for the assessment of the effect of WFD measures to control nitrate at these sites, and hence inform whether investment in treatment would be required within 10 years depending on the success of the WFD measures.

6.6 Organisational responses to the Hybrid-DSP

In answering RQ 4.1, organisational perspectives and responses to the BN based Hybrid-DSP were obtained. Section 2.7 and Section 6.2 previously identified the perspectives of the use of BNs for decision support by the water company. The main points from which are therefore further presented in this section.

With regard to the research conducted, BNs have been used as part of a wider proposed Hybrid-DSP. The use of the multiple techniques coupled with BNs, were perceived by water managers through the reference group meetings to enhance and engender a broader awareness of the problem domain, as reported in Section 4.8.3. Making the link between the impact of the WFD measures on the management of potable water had not been previously undertaken within the water company. Through the use of BNs, a way forward for the prediction and management of future water quality resulting from changes in catchment management practices, due to the WFD, were represented for the first time. Water company representatives were specifically supportive of the development of the BNs (as identified in Section 4.6), as they recognised the benefits of their use to visually integrate multiple variables, in addition to promoting organisational learning of the impact of the WFD on potable water management. Through the use of

BNs, a 'systems view' of the WFD impact on the supply chain was also recognised by managers to be useful, which led to the water managers recognising additional applications of BNs for potable water supply and demand management, as potential future developments. These identified organisational responses, also confirm those found in other studies reporting the benefits of BN use by stakeholders (e.g. Henriksen and Barlebo, 2008) within Europe, and hence, suggest the potential benefits of continued research in this area.

However, during the research, despite the managers recognising the overall benefits of the use of BNs, they also found the mathematical components involved in BNs challenging to understand. Through the research this was addressed by the researcher working closely with the water managers to promote awareness and understanding of the technique, through the discussion of examples during reference group meetings. The issue of the communication of BN modelling has generally been recognised as a limitation when engaging stakeholders (e.g. Castelletti and Soncini, 2007c; Ticehurst and Pollino, 2010), which still requires further development to facilitate wider involvement with stakeholders.

Using the PESTEL framework alongside the development of the BNs led to the development of a shared understanding of the problem domain from different perspectives. This was especially successful in enabling the various technological, regulatory, and strategic perspectives of the reference group members, to be understood and incorporated into the decision making process. During early meetings, the group understanding of the problem domain was dominated by the technological perspective (e.g. the need for technological solutions). These were further developed through the exploration of the wider influencing factors and requirements of the WFD using the 'PESTEL' and 'systems analysis' frameworks to identify other regulatory and strategic perspectives of the problem domain. Hence further gaps in knowledge were identified, which affected the decision-making process through the recognition of alternative actions to be considered (e.g. development of stakeholder engagement activities to understand the activities taking place in source protection zones).

The need to understand the role and interest of stakeholders affecting the management of potable water was also promoted through the analysis of stakeholders by the reference group members. This promoted an understanding of the different types of stakeholders responsible for influencing the nature of the relationships between the variables identified within the BNs produced for the case study catchment. Hence the lack in knowledge of the causal relationship between the presence of diffuse pollution due to activities of specific stakeholders in the catchment, and the impact on potable water supply, was identified to require further investigation. This resulted in the realisation that new knowledge of stakeholder activities and how they affected diffuse pollution in the catchment was needed. Subsequently, the newly identified need to engage with stakeholders led to the first ever 'Diffuse Pollution Forum' organised by Anglian Water, to focus on the role of different stakeholders affecting the management of diffuse pollution in the wider catchment. This was a successful forum which engaged with a wide range of organisational representatives to examine issues linked to the problem of diffuse pollution, and how it could be managed. Therefore, through this research, the importance of understanding the nature and behaviour of stakeholders affecting the operations of the water company, with its specific interest in potable water supply management, was highlighted and contributed to increased stakeholder engagement activities by the water company.

The use of these techniques to understand the problem domain, enabled greater organisational learning and integrated thinking. In addition, communication using the outputs from the exercises conducted (e.g. stakeholder analysis, PESTEL analysis, BNs) with other members of the company through WFD 'Working Group' meetings also enhanced organisational learning and inter-departmental understanding, through the sharing of results from these analyses.

The research highlighted the future use of BNs as a meta-model for the integration of wider knowledge bases, incorporating a transparent and structured approach. This is a timely contribution in the current era of change and the need to manage environmental resources in an integrated and sustainable way. The specific coupling of the identified techniques, and introduction of the use of BNs to a water company presents the first step towards more integrated decision making in the management of water resources. Ultimately through the use of such an approach a more holistic and sustainable perspective in relation to the management of water resources by a water company can be developed, to support the contemporary radical changes in the management of water resources.

7 Conclusions, recommendations and further research

7.1 Responding to the research objectives

The research has attempted to answer four objectives to ultimately achieve the overall aim to "*support the water sector in responding to the implementation of environmental legislation*". The extent to which these objectives have been achieved are summarised within the following paragraphs.

Objective 1: *Review the literature on decision support to understand decision support development, and review the suitability of Bayesian networks as a decision support method for the management of water resources.*

In the review of the literature conducted in Chapter 2, to address RQ 1.1 and 1.2, it was identified that there has been an acceleration in the use of BNs as a decision support mechanism. A significant driver behind the recent developments, clearly was the requirements of WFD. Studies concentrated on the ability of BNs to support 'participatory' and 'integrated' decision making. However, only a few articles have specifically explored the implications of WFD PoMs on the management of water quality within the environment. The role which BNs have to support decisions in relation to environmental legislation implementation has mostly been recognised in supporting regional or catchment based policy development. These applications have been found to be successful in involving multiple stakeholders in collaboratively using BNs to focus discussions in relation to the variables affecting the management of water resources. BNs have also been used as a vehicle to negotiate conflicting priorities between stakeholders, enabling the representation of the impacts of different decisions on the management of water resources. Gaps in the literature in relation to the use of BNs for decision support were identified. There included limited publications on organisational responses to the use of BNs; limited application of BNs to water quality management (instead a dominant focus has been on water quantity management); and limited integration of both water quality and quantity aspects. In addition, there was an absence of literature related to organisational applications of BNs for WRM.

In light of the recognised benefits of using BNs, but with awareness of the highlighted deficiencies, the development of the Hybrid-DSP provided the opportunity to assess the applicability of BNs to a complex problem domain within a specific case study organisation.

Objective 2: *Review existing organisational decision processes for potable water resource management within the case study organisation.*

The existing systems within the case study organisation were reviewed in relation to RQ 2.1 and 2.2. The review identified that these were not adequate to integrate the WFD PoMs and assess the impacts on potable water management. The existing systems were focused on specific elements of water management (e.g. physical risks to water quality), with historical evidence being used to justify future investments. The integration of the impact of future changes to the way in which water resources are managed within the catchment through environmental legislation was not evident. Hence further development of a new decision support process to facilitate an assessment of environmental legislation implementation and the implications for potable water management, was identified and recognised by both the researcher and the water managers.

Objective 3: *Develop a decision-support process to explore and assess the organisational implications of the Water Framework Directive on potable water management.*

In answering RQ 3.1 – 3.4, Research Objective 3 was achieved. The requirements for a decision support process were identified through liaison with the case study organisation, through interviews and reference group meetings. BNs, as an emerging identified technique for WRM in relation to the WFD implementation, as discussed in Chapter 2, was selected as the focus of the development of a Hybrid-DSP. Additional strategic management techniques were also identified from the strategic management literature and implemented to support the understanding of the problem domain. These techniques were coupled resulting in a Hybrid-DSP. Within Chapter 5, the new Hybrid-Decision Support Process (DSP) was demonstrated using the problem domain of nitrate contamination in groundwater used for potable water supply. This new Hybrid-DSP is proposed as a participatory decision support tool for application within the UK water sector to inform integrated organisational strategic responses to the implications of environmental legislation.

Objective 4: *Identify organisational responses to the decision support process*

In answering RQ 4.1, organisational responses to the Hybrid-DSP were obtained through observations made by the researcher during reference group meetings and during interviews. Organisational responses to the proposed Hybrid-DSP were supportive, and the potential which BNs as a central tool had to support decisions for potable water resources management, was recognised. Although the study had focused on the water quality problem of nitrate, the water managers also recognised the potential to apply the Hybrid-DSP to other water quality issues (e.g. pesticides) as well as water supply and demand management. The use of problem characterisation methods were further identified by water managers to promote a wider understanding of the problem domain. These combined approaches facilitated increased learning and understanding by the water managers of the inter-relationships between the variables and the nature of the spheres of influence of relevant stakeholders. Consequently, alternative organisational investment options in response to the WFD implementation for potable water resource management, as opposed to water treatment, were able to be identified and their potential impact explored through the use of the proposed techniques.

Therefore the contributions to knowledge resulting from this study are:

1) **The demonstration of a new proposed BN based Hybrid-DSP** to facilitate the development of integrated organisational responses for the management of potable water supply in relation to the WFD implementation.

2) **The gaining of extensive organisational responses from within a case study organisation on the use of a BN based Hybrid-DSP as a means to inform the management of potable water.** Organisational responses to the use of BNs were positive with indications made for their future application to model the implications of the WFD for water quality at further WTW sites. It was recognised that the process had the potential for application to other areas of water management, for example supply and demand management. The extent of resources required to implement BNs for multiple sites however, was a concern, in response to which the organisation indicated its use would initially be for priority sites.

3) **The development of a process (Hybrid-DSP) that promotes organisational learning.** This was particularly evident through the visual representation of the integrated relationships between variables within the problem domain. In addition, the ability to develop BNs through consultation with the managers and the use of the additional techniques encouraged a participatory approach, which further generated organisational learning. Both these aspects align with the approach required by the WFD for decision making in relation to water resource management.

7.2 Limitations of the study

The limitations of the study undertaken are highlighted below, from both a practical and academic perspective:

- The study was conducted using only one water company, and therefore the findings identified may not be representative or reflective of the rest of the UK water sector. Further applications using the Hybrid-DSP approach would be required to establish wider organisational perspectives of the use of the proposed approach.
- No liaison or engagement with the UK water sector regulators (Ofwat, EA, DWI) was made directly in relation to the use of the techniques used within the

Hybrid-DSP, therefore the acceptability of the techniques to support decision making by the regulators requires further research.

- The case study used to apply the BN was a groundwater quality problem, other case studies focusing on other water quality or water quantity issues would be required in order to support the use of the Hybrid-DSP across a broader range of case study application contexts.
- The stakeholders involved within the company were limited to the main reference group of water managers. Further involvement with a broader range of water company representatives would give more credibility of the Hybrid-DSP within the case study company.
- The software Hugin used to undertake the BN development was restricted in use to the researcher. A further licence was not obtained for its use within the company to enable potential end-users to explore its use directly.
- The WFD was the only environmental legislation considered within this study, although further environmental legislation could be also used to test the Hybrid DSP approach.

The implementation of the BN based Hybrid-DSP will ultimately be subject to the development of internal knowledge and capability to use the BN software, and work collaboratively between departments. Potential organisational changes, water managers availability, time available to complete BNs for specific sites and potential changes in the role or presence of water managers within the company where knowledge of BNs and the Hybrid-DSP process leaving the organisation remain a threat to the application and implementation of the BN based Hybrid-DSP approach. Further training in the use of BNs, would also need to be provided to support the organisation in building internal capability. This would need to be conducted over a period of months with future continued support where new BNs are required or where existing BNs are to be modified.

7.3 Further research opportunities

Opportunities identified for further research to extend and develop the Hybrid-DSP and its application include:

- Further application of Hybrid-DSP to both surface water and groundwater quality and quantity problem domains to test the extent of the use of the proposed Hybrid-DSP.
- Further research and development of methods to elicit CPTs within a water company to provide a standardised approach which is transparent and identifies the sources of uncertainty in the data sources and data used.
- Further development of the Hybrid-DSP as a software tool with a user-friendly interface to select and manage ‘factors’ and subsequent ‘variables’ in the process of the development of the BNs. Hence providing a transparent and auditable approach for the justification of proposed investment.
- Involvement of multiple stakeholder groups (including external regulators and local site specific stakeholders) in the use of the Hybrid-DSP to encourage further learning and understanding of the factors affecting the sustainable management of water resources.

7.4 Key recommendations

The recommendations resulting from the conduct of this research involve the further application of the BN based Hybrid-DSP within a UK water company. In undertaking this recommendation the following points should be addressed:

- Use of an independent facilitator during meetings and workshops with water company representatives from different departments to encourage participation and organisational learning during the implementation steps of the Hybrid-DSP.
- Bayesian network software needs to be available within the company for use and application by water managers, initially on a non-networked laptop computer, with a limited licence for several users. This would enable the software to be used and demonstrated within workshops and meetings within the company.

- Specific end-users within the organisation should be identified within the water resources team to undertake training in the use of the BN technique and related software (e.g. Hugin A/S Expert).
- The Hybrid-DSP approach should be undertaken with managers who focus on the strategic issues affecting potable water management, as well as with site specific water treatment works managers to establish local operational issues.
- Phase 2 of the Hybrid-DSP should be conducted for each site separately and revised on an annual basis, to update beliefs within the CPTs. The BNs for specific sites should also be updated when specific 'trigger' events occur (e.g. water quality incidents/ water quantity incidents –floods/ droughts).

The Hybrid-DSP offers a new approach to the holistic and integrated assessment of factors affecting potable water management, including environmental legislation, and hence contributes towards the sustainable management of potable water. The sustainability of maintaining a potable water supply is a critical concern affecting organisations responsible for supplying potable water. The future availability and treatment requirements remain uncertain, and are dependent on many complex and interrelated factors. Without the development of processes such as the Hybrid-DSP to holistically assess the future implications affecting potable water supply, achieving the objective of sustainable water management would be compromised. Through conducting further applications of the proposed Hybrid-DSP the extent of the resources required for its implementation and the use of the process in practice could be further established and contribute to more sustainable management of potable water supplies.

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Appendix

Contents

Appendix A

Summary tables of Bayesian network literature

The tables below provide a summary of the literature reviewed on Bayesian networks referred to in this thesis. The case studies are presented together with the associated references.

App Table 1: Overview of the case studies and references reviewed within the thesis on the use of BNs for water resources management

Case Study	Issue	Qual	Quan	GW	SW	WFD	Part	References
Havelse Wellfield catchment, North Zealand, Copenhagen, Denmark. (MERIT project)	Pesticide pollution of groundwater supply to Copenhagen (Catchment, DOMESTIC SUPPLY)	✓	✗	✗	✓	✓	✓	Henriksen *et al* (2007d); Henriksen *et al* (2007c); Henriksen *et al* (2004); Henriksen and Barlebo (2008).
Havelse Wellfield catchment, North Zealand, Copenhagen, Denmark. (NeWater project)	Pesticide pollution of groundwater supply to Copenhagen (Catchment, DOMESTIC SUPPLY)	✓	✗	✓	✗	✓	✓	Farmani *et al* (2009); Henriksen et al (2007a); Henriksen and Barlebo (2008).
Sultanate of Oman, water supply	Water quality in monitoring wells for domestic water supply (Total dissolved solids, electrical conductivity, pH, Chemical oxygen demand, and nitrate). (Catchment, DOMESTIC SUPPLY)	✓	✗	✓	✗	✗	✗	Shihab and Chalabi (2007); Al-Chalabi and Shihab (2008)
Kerava River, southern Finland.	Evaluation of river quality forecasting systems within the catchment, and the river.	✓	✗	✗	✓	✗	✗	Varis *et al* (1993)
Lac de Guiers, on the Senagal River in West Africa	Salinity, eutrophication, macrophytes, schistosomiasis and malaria. (catchment, abstraction, and the supply of water)	✓	✗	✗	✓	✗	✗	Varis and Fraboulet-Jussila (2002)
Neuse River Estuary,	Chlorophyll dynamics in the estuary (catchment, and estuary), using	✓	✗	✗	✓	✗	✗	Alaeddine *et al* (2011)

Case Study	**Issue**	**Qual**	**Quan**	**GW**	**SW**	**WFD**	**Part**	**References**
North Carolina, USA	structural learning to develop BN.							
Lake Storefjordan, Morsa catchment, South-East Norway.	Phosphorous in catchment, impact of eutrophication on water quality, and abatement measures as part of the WFD – economic analysis (catchment level)	✓	×	×	✓	✓	×	Barton *et al* (2005); Barton *et al* (2008)
Susquehanna River Basin (SRB) in Pennsylvania, USA	(water treatment, DOMESTIC SUPPLY)	✓	×	×	✓	×	✓	Pike (2004)
Coastal Lakes in New South Wales, Australia	Sustainability of coastal lakes	✓	×	×	✓	×	✓	Ticehurst *et al* (2007)
Eastern Mancha aquifer unit, part of the Upper Guadiana Basin, south-east of the Iberian Peninsula, Spain (MERIT project)	Competition for water between domestic, environmental and agricultural sectors. Over exploitation of an aquifer (the Hydrogeological Unit Eastern Mancha [HUEM]), which includes the aquifer known as "Eastern Mancha", due to irrigation (CATCHMENT, ABSTRACTION, IRRIGATION DEMAND) *(✓) = ONLY RELATED TO POTENTIAL SW INVESTMENT OPTIONS*	×	✓	✓	(✓)	✓	✓	Martin de Santa Olalla *et al* (2005) Martin de Santa Olalla *et al* (2007)
Western Mancha Occidental Aquifer, Upper Guadiana basin, Spain (NeWater project)	Over exploitation of aquifer, due to irrigation. (CATCHMENT, ABSTRACTION, IRRIGATION DEMAND)	×	✓	✓	×	✓	✓	Zorrilla *et al* (2007); Carmona and Varela-Ortega (2007)
Mancha Occidental Aquifer, Upper Guadiana basin, Spain (central plateau of Spain encircled by the Tajo, Jucar and Guadalquivir Basins) (NeWater project)	Management of irrigation water for farming and domestic supplies. Over exploitation of aquifer, due to irrigation and impact on wetlands. (CATCHMENT, INDUSTRY DEMAND FOR IRRIGATION)	×	✓	✓	×	✓	✓	Henriksen *et al* (2007b); Martínez-Santos *et al* (2010); Zorrilla *et al* (2010); Carmona *et al* (2011a); Carmona *et al* (2011b).
Altiplano Water System (northern part of Murcia Province in South East Spain) Spain (NeWater project)	Over exploitation of four hydraulically separate aquifers. An extreme case of intensive groundwater use. (CATCHMENT, INDUSTRY DEMAND FOR IRRIGATION)	×	✓	✓	×	✓	✓	Carmona *et al* (2011a); Molina *et al* (2009); Molina *et al* (2010); Molina *et al* (2011a); Molina *et al* (2011b)
Hydrogeological unit –	Water demand management (CATCHMENT, ABSTRACTION,	×	✓	✓	(✓)	×	×	Asadilour *et al* (2012)

Case Study	**Issue**	**Qual**	**Quan**	**GW**	**SW**	**WFD**	**Part**	**References**
Tehran City, in Iran	SUPPLY OF WATER) *(✓) = DAMS AND GW SOURCES USED)*							
Lake Maggiore Project, Cross-borders Italy and Switzerland (INTERREG II-EU framework project)	Water demand and flood management, used BN as part of the PIP process and coupled with other methods. (CATCHMENT, WATER DEMAND BY FARMERS).	×	✓	×	✓	×	✓	Castelletti and Soncini-Sessa (2006); Castelletti and Soncini-Sessa (2007a)
Vomano water system, Abruzzo river basin, central Italy. (MERIT project)	Competing requirements for water from Hydropower, and domestic supply. Reservoir management, integrating farm irrigation, domestic, and environmental demands for water, with energy production by the hydro power company.(CATCHMENT, RIVER, LAKE, ABSTRACTION, WATER TREATMENT, WATER SUPPLY)	×	✓	×	✓	✓	✓	Castelletti A., Soncini-Sessa R. (2007c)
Bikram Bagh Khul irrigation system, in the Shiwalik region of the Indian Himalayas	Irrigation management, diverting water from river into a gravity-based system that consists of a network of primary, secondary and tertiary lined or earthen channels. (CATCHMENT, RIVER)	×	✓	×	✓	×	✓	Saravanan (2008); Saravanan (2010)
Neuse River estuary, North Carolina, USA	Eutrophication of the estuary as a result of elevated nitrogen concentrations (CATCHMENT)	✓	✓	×	✓	×	×	Reckhow *et al* (1999)
Senagal River in West Africa	IWRM along the Senegal River (five groups of variables; general tendencies, river valley policies, environmental impacts, socio-economic impacts, stakeholders) (CATCHMENT, ABSTRACTION, SUPPLY OF WATER)	✓	✓	×	✓	×	×	Varis and Lahtela (2002);
Watershed management in East Canyon Creek, Utah, USA.	Phosphorous in surface water, and catchment.	✓	✓	×	✓	×	×	Ames *et al* (2005)
Tonle Sap Lake, Cambodia	Policy analysis for water resources management within Tonle Sap Lake, analysing development goals of economic, environmental sustainability and poverty reduction. (CATCHMENT,)	✓	✓	×	✓	×	✓	Varis and Keskinin (2006)
The Big Lost River, south–central Idaho, USA	Physical and economic sustainability of water. Flow regulation within the “Big Lost River” in south-central Idaho, to reduce river pollution and restore the water bodies. Management options include: construction of reservoirs and lining canals. (CATCHMENT, RIVER, LAKE, INDUSTRIAL IRRIGATION)	✓	✓	×	✓	×	×	Said *et al* (2005); Said (2006a); Said *et al* (2006b)

Case Study	**Issue**	**Qual**	**Quan**	**GW**	**SW**	**WFD**	**Part**	**References**
Gaza Strip	desalination plant operation for potable water supply	✓	✓	✗	✓	✗	✗	Ghabayen *et al* (2004)
Hongulia Catchment, Solomon Islands	Management of whole catchment, social, economic, technical, political, environmental variables. (CATCHMENT, ABSTRACTION, WATER TREATMENT, WATER SUPPLY, WASTEWATER TREATMENT).	✓	✓	✓	✓	✗	✓	Chan *et al* (2008); Chan *et al* (2010)
Note: Qual= water quality; Quan = Water quantity; GW =groundwater' SW = surface water; WFD = Water Framework Directive; Part = Participatory approach; ✓ = included, (✓) =partially included, ✗ = not included in case study.								

App Table 2: Overview of case studies and references for UK applications of BNs for water resources management

Case Study	Issue	Qual	Quant	GW	SW	WFD	Parti	References
Loddon catchment (South East England, Portsmouth area)	Apply BN - Integrated water resources management, focus on domestic water demand management strategies. [EU MERIT project]	✗	✓	✗	✓	✓	✓	**Bromley *et al* (2005)**
Don Catchment, (North of England, Sheffield area)	Apply a newly developed integrated Meta-model approach (which includes BN) called the Macro-Ecological Model (MEM) – part of Integrated catchment management (ICM) focus on urban drainage, floods, and agricultural land.	✗	✓	✗	✓	✓	✓	**Kumar *et al* (2010); Holzkämper *et al* (2012) [Lerner *et al*, 2011]**
Don Catchment, (North of England, Sheffield area)	Apply BN - Integrated Catchment management – Weir Management: Design of weirs within an urban river environment incorporating views of canoeists'. (focus on social issues).	✗	✓	✗	✓	✗	✓	**Shaw *et al* (2010)**
Don Catchment, (North of England, Sheffield area)	Develop new method (combining an interactive 3D landscape design, software tool with a BN) - Integrated Catchment management – Weir Management: Design of weirs within an urban river environment incorporating the perspectives of canoeists'.	✗	✓	✗	✓	✗	✓	**Gill *et al* (2010)**

Note: Qual= water quality; Quan = Water quantity; GW =groundwater' SW = surface water; WFD = Water Framework Directive; Part = Participatory approach; ✓ = included, ✗ = not included in case study.

App Table 3: Summary of BN articles for water management (including UK) categorised according to the focus of the BN application and the specific case studies

	Groundwater	Surface water	Both
Water quality	**Denmark: Havelse Wellfield catchment, North Zealand, Copenhagen:** *[Henriksen et al (2007d); Henriksen et al (2007c); Henriksen et al (2004); Henriksen and Barlebo (2008); Farmani et al (2009); Henriksen et al (2007a); Henriksen and Barlebo (2008)]* **Oman: Sultanate of Oman:** *[Shihab and Chalabi (2007); Al-Chalabi and Shihab (2008)]*	**Australia:** *[Ticehurst et al (2007, McDowell et al, 2009)]* **Finland case study:** [*Varis et al (1993)]* **Norway:** *[Barton et al (2005); Barton et al (2008)]* **USA:** [*Alaeddine et al (2011)]* **USA, Pennsylvania:** [*Pike (2004)][T]* **West Africa:** *[Varis and Fraboulet-Jussila (2002)]* **Gaza Strip:** *[Ghabayen et al., 2004][T]* ***None specified:*** *[Zhu and McBean, 2007][T]*	No studies reviewed
Water quantity	**Spain: Western Mancha Occidental Aquifer, Upper Guadiana basin :** *[Zorrilla et al (2007); Carmona and Varela-Ortega (2007)]* **Spain: Mancha Occidental Aquifer, Upper Guadiana basin:** *[Henriksen et al (2007b); Martínez-Santos et al (2010); Zorrilla et al (2010); Carmona et al (2011a); Carmona et al (2011b).]* **Spain: Altiplano Water System (northern part of Murcia Province in South East Spain):** *[Carmona et al (2011a); Molina et al (2009); Molina et al (2010); Molina et al (2011a); Molina et al (2011b)]*	**Indian Himalayas: Bikram Bagh Khul irrigation system, in the Shiwalik region :** *[Saravanan (2008); Saravanan (2010)]* **Italy/Switzerland: Lake Maggiore Project, Cross-borders :** *[Castelletti and Soncini-Sessa (2006); Castelletti and Soncini-Sessa (2007a), Castelletti and Soncini-Sessa (2007b)]* **Italy: Vomano water system, Abruzzo river basin:** *[Castelletti A., Soncini-Sessa R. (2007c)]* **UK: Loddon catchment:** *Bromley et al (2005);* **UK: Don Catchment:** *Kumar et al (2010); Holzkämper et al (2012); Shaw et al (2010); Gill et al (2010)*	**Iran: Tehran City:** *[Asadilour et al (2012)]* **Spain: Eastern Mancha aquifer, Iberian Peninsula:** *[Martin de Santa Olalla et al (2005); Martin de Santa Olalla et al (2007)]*
Both	No studies reviewed	**Cambodia: Tonle Sap Lake:** *[Varis and Keskinin (2006)]* **Gaza Strip: Seawater desalination:** *[Ghabayen et al, 2004]* **USA: Neuse River estuary, North Carolina:** *[Reckhow et al (1999)]* **USA: Big Lost River Watershed in south-central Idaho:** [*Said et al (2005); Said (2006a); Said et al (2006b)]* **USA: East Canyon Creek, Utah:** *[Ames et al (2005)]*	**Solomon Islands: Hongulia Catchment:** *[Chan et al (2008); Chan et al (2010)]* **West Africa:** [*Varis and Lahtela (2002)]*

Note: [T] indicates reference to BN used for water treatment

App Table 4: Summary of articles concerned with either industrial or domestic water supply

	Industrial water supply	Domestic water supply
Water quality	**GW:** No studies reviewed **SW:** No studies reviewed **Both GW and SW:** No studies reviewed	**GW: Physiochemical properties** [*Shihab and Chalabi (2007); Al-Chalabi and Shihab (2008)*] **GW: Pesticide contamination** [*Henriksen et al (2004); Henriksen et al (2007a); Henriksen et al (2007d); Henriksen et al (2007c); Henriksen and Barlebo (2008); Farmani et al (2009).]* **SW: Compliance failure** [*Pike (2004)] [T]* **SW: Treatment requirements** *[Ghabayen et al., 2009] [T]* **Both GW and SW:** No studies reviewed **No specific source:** *[Zhu and McBean, 2007][T]*
Water quantity	**GW: Irrigation of farmland** *[Martin de Santa Olalla et al (2005); Martin de Santa Olalla et al (2007) Carmona and Varela-Ortega (2007);* Zorrilla et al (2007); *Henriksen et al (2007b); Molina et al (2009); Martínez-Santos et al (2010); Molina et al (2010); Zorrilla et al (2010); Carmona et al (2011a); Molina et al (2011a); Molina et al (2011b); Carmona et al (2011a); Carmona et al (2011b).]* **SW: Hydropower** Varis and Lahtela (2002); Castelletti A., Soncini-Sessa R. (2007c); **SW: Irrigation of farmland** Varis and Lahtela (2002); Castelletti A., Soncini-Sessa R. (2007c)] **Both GW and SW:** No studies reviewed	**GW:** No studies reviewed **SW: Availability** *Bromley et al (2005)* [*Varis and Lahtela (2002)*] [Asadilour et al, 2012] **SW: Cost of domestic supply** [*Castelletti A., Soncini-Sessa R. (2007c)]* **Both GW and SW:** No studies reviewed
Both	**GW:** No studies reviewed **SW: Irrigation** [Said et al (2005); Said (2006a); Said *et al* (2006b)] **Both GW and SW:** Chan et al (2008); Chan et al (2010)	**GW:** No studies reviewed **SW: Desalination plant operation** Ghabayen et al (2004) *[T]* **Both GW and SW:** Chan et al (2008); Chan et al (2010)
Note: [T] = water treatment application		

App Table 5: Articles focused specifically on surface water quality at the catchment, abstraction and treatment level

Catchment level	Abstraction level	Water treatment
Varis *et al*, 1993; Varis and Fraboulet-Jussila, 2002; Ames *et al*, 2005; Barton *et al*, 2005; Ticehurst *et al*, 2007; Barton *et al*, 2008; McDowell *et al*, 2009; Alameddine *et al*, 2011.	Varis and Lahtela, 2002; Asadilour *et al*, 2012.	Ghabayen *et al*, 2004; Pike, 2004; Zhu and McBean, 2007.

Appendix B

Planning cycles for the UK water sector and the WFD

App Table 6: Comparison of the planning cycles for UK water companies and the implementation process of the WFD

Timeline	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
Water Sector Cyclical Plans																														
Ofwat Periodic Review (PR yr)	PR04					PR09					PR14					PR19					PR24					PR29				
Water Company Asset Management Plans (AMP)	AMP3					AMP4					AMP5					AMP6					AMP7					AMP8				
Environment Agency National Environment Programmes (NEP)				NEP					NEP					NEP					NEP					NEP					NEP	
Water Framework Directive: Requirements																														
Prevention and control of GW pollution (Art 5,11,17)																														
Member State legislation (Art.24)																														
Identification of competent authorities (Art 3)																														
Geographic identification of river basins (Annex I)																														
River Basin Characterisation (Art.5) & (Annex II, III)						Review																								
Register of protected areas (Art 6, 7(i), Annex IV)						Review																								
Monitoring Programmes established (Art.8, 21, Annex V)								Continue Monitoring																						
WFD RBMP Cycles (art 14, 13 & VIII)					Draft RBMP						RBMP 1						RBMP 2						RBMP 3							
Programme of Measures (PoM) (Art. 11, VI)								Draft PoM			Operational				Review		Operational				Review		Operational				Review			
Recovery of costs for water services (Art.9, III)							Economic assessment					Review																		
Emissions, point and diffuse source pollution controls best practice implemented (Art.10)								Pollution controls implemented						Review																

Appendix C

Organisation and informant details

The following tables present the references for the informants who contributed to the research being undertaken. Throughout the thesis the reference numbers are used to refer to reference group meetings (e.g. RG 1), focus groups (e.g. FG 1), semi-structured interviews (e.g. INT 1), informal discussions/ meetings (e.g. IM 1) and individual informants (e.g. ID 1). These details are presented within this appendix.

In total 49 individuals from within the case study organisation contributed to the research, in addition to 33 individuals from outside the organisation, representing nine different organisations.

App Table 7: General reference list for informants who contributed to the research

Reference No.	Organisation	Role
ID1	Water Company A	Biosolids sales manager
ID2	Water Company A	Climate Change Scientist
ID3	Software Consultancy	CEO
ID4	Water Company A	Climate Change and Environmental Performance Manager
ID5	Water Company A	Customer Relations
ID6	Academic institution	Senior Research Fellow
ID7	Academic institution	GIS Developer
ID8	Water Company A	DWSP
ID9	Water Company A	Innovation Programme Manager - Clean Water
ID10	Water Company A	Regional Quality Manager
ID11	Academic institution	Lecturer and Water Programme Leader
ID12	Academic institution	Senior Lecturer - School of Management
ID13	Water Company A	Drinking Water Quality
ID14	Environmental Consultancy B	Modeller
ID15	Water Company A	Innovation technologist
ID16	Water Company A	Head of Water Quality and Environmental Performance
ID17	Environmental Consultancy B	Water Sector Manager
ID18	Water Company A	Media Manager
ID19	Water Company A	Strategic Scientist
ID20	Water Company A	Strategic Scientist
ID21	UK Government Agency A	Principle Officer for Anglian River Basin District (RBD) Compliance Manager
ID22	Water Company A	Regulatory Water Resources Manager
ID23	Water Company A	Maintenance manager (Barrow WTW)
ID24	Academic institution	Research Student
ID25	Academic institution	Principal Research Fellow
ID26	Water Company A	Innovation - Clean Water
ID27	UK Government Agency A	River Basin Programme Manager for Anglian Region.
ID28	UK Government Agency C	Catchment Sensitive Farming Officer, East riding of Yorkshire and North East Lincolnshire Catchment
ID29	Environmental Consultancy A	Associate Director
ID30	Water Company A	Hydrology Manager
ID31	Water Company A	Environmental Standards Team Leader
ID32	Water Company A	Biosolids mgr North West area

Reference No.	Organisation	Role
ID33	Water Company A	Asset Investment Manager
ID34	Water Company A	Strategic Investment Manager
ID35	Water Company A	Wastewater Quality Manager
ID36	Academic institution	Research student
ID37	Academic institution	Professor in resource economics and management
ID38	Water Company A	Managing Director
ID39	Asset Management Consultancy	Director
ID40	Water Company A	Customer Relations
ID41	Water Company A	Environmental Strategy Scientist
ID42	Water Company A	Water supply manager
ID43	Water Company A	Industrial Process Engineer
ID44	Water Company A	Business Customer Services Manager
ID45	Asset Management Consultancy	Director
ID46	Water Company A	Customer response manager
ID47	Water Company B	Head of water resources and supply
ID48	Water Company A	Environmental regulation manager
ID49	Academic institution	Research Student
ID50	Water Company A	Consents Manager
ID51	Water Company A	WTW Mgr
ID52	Academic institution	Lecturer
ID53	Water Company A	Asset Planning Manager
ID54	Academic institution	Senior Lecturer
ID55	Water Company A	Manager of Water Resources
ID56	UK Government Agency A	Catchment Sensitive Farming Officer
ID57	Water Company B	Catchment site Manager
ID58	Academic institution	Research Student
ID59	Water Company A	Project Manager - Risk and Value/ Business Improvement Manager
ID60	Academic institution	Senior Research Fellow
ID61	Academic institution	Professor of Water Management
ID62	Water Company A	Investment Manager
ID63	Water Company A	Head of Water services
ID64	Water Company A	Environmental Consents Team Leader
ID65	Water Company A	WWTW Site Mgr
ID66	Academic institution	Reader in Water and Environmental Law
ID67	Water Company A	Investment Manager
ID68	Academic institution	Senior Lecturer in Strategic Management
ID69	Water Company A	Innovation Project Manager
ID70	Water Company A	Principle Scientist

Reference No.	Organisation	Role
ID71	UK Government Agency B	Farm conservation advisor
ID72	Water Company B	Environmental Regulation Manager
ID73	Water Company A	Groundwater Manager - Catchment Manager
ID74	Academic institution	Professor of Environmental Risk Management
ID75	Academic institution	Principal Research fellow in Soil Resource Informatics
ID76	Water Company A	Manager of Innovation
ID77	Water Company A	Water supply and demand strategy manager
ID78	Water Company A	Water supply manager
ID79	Water Company A	Biosolids Manager
ID80	Academic institution	Research Student
ID81	Water Company A	Project Manager
ID82	Water Company A	Strategic Scientist (Asset Mgt)

App Table 8: list of organisations who contributed to the thesis

Organisation	Anonymous terminology	Number of informants from each organisation
A	Water Company (A)	49
B	Water Company (B)	3
C	Environmental Consultancy (A)	1
D	Environmental Consultancy (B)	2
E	Software Consultancy	1
F	Asset Management Consultancy	2
G	UK Government Agency (A)	3
H	UK Government Agency (B)	1
I	UK Government Agency (C)	1
J	Academic institution	19
Total number of organisations:		**Total number of informants:**
10		**82**

A total of 10 organisations (including AWS) and 82 informants contributed to the research.

Appendix D

Interview guides used for semi-structured interviews

The interview guides used to conduct the interviews are presented in this Appendix. These include two guides, for two phases of interviews, one in September 2008 and another in September 2009. The details for the two interview phases are presented in the following sections.

<u>September 2008 semi-structured interviews</u>

The first phase of interviews were to follow up on the development of both the PESTEL framework and the development of the stakeholder analysis through the identification of ecosystem functions as related to the specific stakeholder groups identified by the individual members of the steering group during the workshop on the 13th August 2008. This allowed for the open exploration of the specific issues affecting the management of water resources to be explored, together with the stakeholders which may have an influence or interest in the management of the water resources.

The selected participants were from within the reference group and familiar with the nature of the research, and the techniques to be considered within the interview. The purpose of the interview was verbally explained at the start, followed by semi-structured questions working through the main themes within the PESTEL analysis (Johnson and Scholes, 2002, Johnson *et al*., 2008), and the exploration of the stakeholders associated with these PESTEL factors using the stakeholder classification as per de Groot (2002, 2006) definitions. The PESTEL and stakeholder questions were followed up by the researcher to explore the perceptions of the issues identified by the participant.

The definitions presented in the tables below, were used to categorise the responses made by the participants in the interviews during the first part of the interview (PESTEL categories) and the second part of the interview where participants were asked to identify the stakeholders and discuss the importance of the stakeholders in relation to the decision making process for the management of potable water. The classifications identified by de Groot were used as a focus for discussion regarding the specific functions of the stakeholder groups.

App Table 9: Generic PESTEL factors (adapted from Johnson and Scholes, 2002:102)

PESTEL Factors	Description
Political	Highlights the role of governments e.g. Government Stability/ Taxation Policy /Foreign trade regulations/ Social Welfare policies.
Economic	Mainly concerned with macro-economic factors: e.g. Business cycles/ GNP trends/ Interest rates/ Money Supply/ Inflation/ Unemployment/ Disposable income
Sociocultural	Changes in cultures and demographics: e.g. Population demographics/ Income distribution/ Social mobility/ lifestyle changes/ attitudes to work and leisure/ consumerism/ levels of education.
Technological	The changes in technological developments: e.g. Government spending on research/ Government and industry focus on technological effort/ new discoveries and developments/ speed of technology transfer/ rates of obsolescence
Environmental	Specifically related to `green` issues: e.g. Environmental protection laws/ pollution and waste disposal/ energy consumption
Legal	Legislative constraints or changes: e.g. Monopolies legislation/ employment law/ health and safety/ product safety.

App Table 10: Ecosystem functions adapted from de Groot *et al* (2002,2006)

Stakeholder function	Description
Regulation	Regulate the local and global energy balance
Habitat	The environmental requirements needed
Production	Raw materials for building/ construction/ resources
Carrier	Provide space and suitable substrate for; human habitation/ cultivation (crops/ animals/aquaculture)/ energy conversion/ nature protection/ recreation & tourism
Information	Aesthetic info/ spiritual and religious info/ historic info/ cultural artistic inspiration/ scientific and educational information.

<u>September 2009 semi-structured interviews</u>

These interviews were conducted with an interview template which was sent out to the research participants prior to the interview. The template is presented as below.

<u>Research participant semi-structured interview template</u>

Overview and purpose

The following questions are to provide triangulation and verification of evidence to support both *the need* for the research, through an identification of *the GAP* in the current business activities, and for the identification of the *end user requirements* and *evaluation criteria* for any proposed decision support framework developed as part of this research.

- Questions 1, 2 and 3 will help to inform a **SWOT analysis** of the current system and its operation.
- Questions 4 and 5 will allow for the identification of the **requirements and decision criteria** to be considered and developed within the research to inform a decision support system.
- Questions 6 and 7 will allow for the identification of the perceived **impact of the WFD on water resources management** and specifically potable water treatment requirements.

The interview is a *semi-structured interview* which allows for an initial question to be posed and further elaboration of the subject/ area to be considered and further discussed.

<u>Current performance of the business:</u>

Q1a: What is the current Anglian Water investment decision making process?

Q1b: How does AWS identify the implications of the EU WFD?

Q1c: Does AWS specifically identify the impact of the WFD on potable water resource management and treatment requirements?

<u>Assessment of Current Performance:</u>

Strengths and Weaknesses

Q2a: What are the strengths of the current decision making process?

Q2b: What are the weaknesses with the current decision making process, and hence what aspects need further improvement?

Opportunities and Threats

Q3a: What opportunities exist from within the current investment system, which may be further developed/ built on?

Q3b: What are the threats to the business of the current investment decision making process?

End user requirements

Q4: What end user requirements would you specify for a newly developed decision support framework for investment decision making?

Assessment criteria

Q5: What assessment criteria can be identified to evaluate a newly developed Decision Support Framework?

Impact of the WFD on potable water resources

Q6: What is the impact of the WFD on *potable water resources management*?

Q7: What is the impact of the WFD on *potable water treatment requirements*?

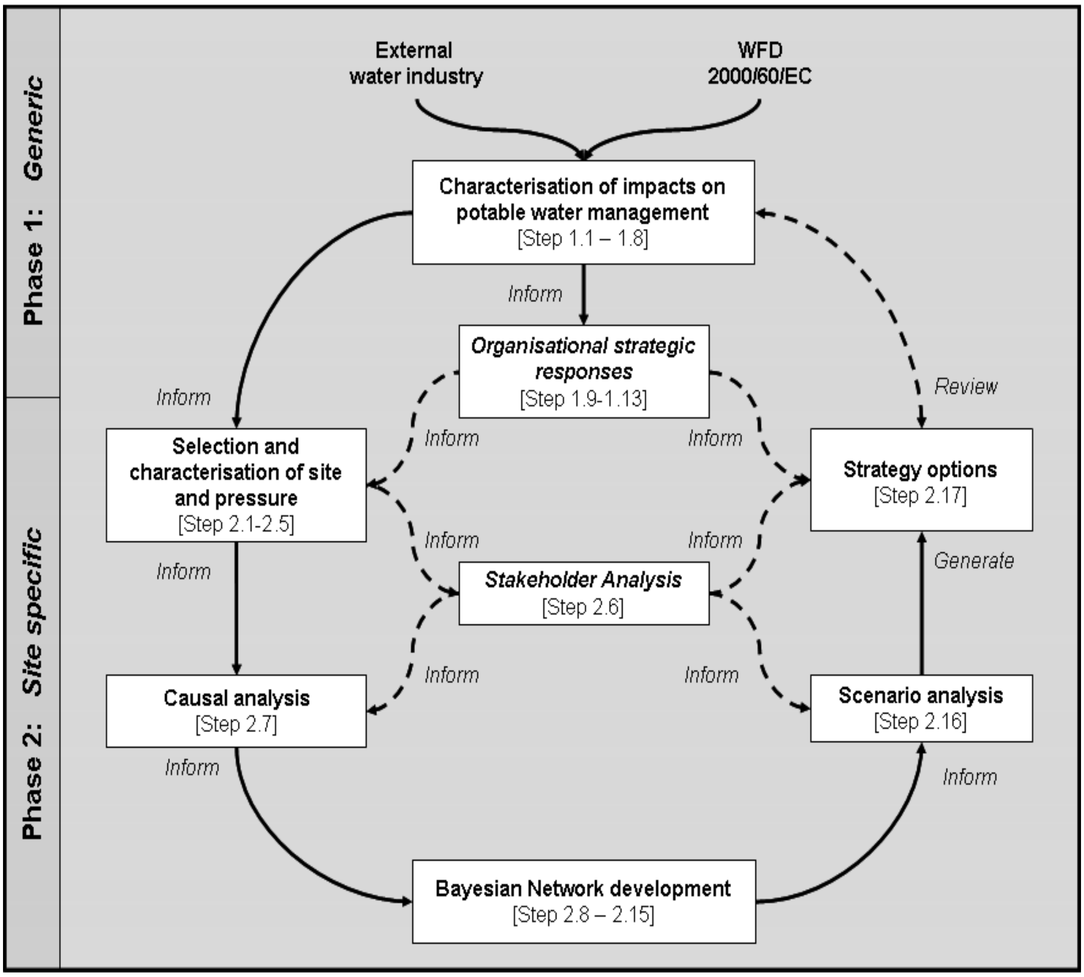
The information provided in this interview will support other evidence gained from previous informal interviews, observations together with academic and company literature, to provide a specific perspective from the water company regarding the key issues.

Appendix E

Hybrid-DSP user manual

The Hybrid-DSP

The Hybrid-DSP provides strategic decision support to develop organisational understanding under conditions of uncertainty and complexity to inform strategic options for potable water management in response to the implementation of the WFD. The main process stages are presented in App Figure 1.



App Figure 1: The Hybrid-DSP process

Hybrid-DSP implementation approach

When should it be used?

The use of the Hybrid-DSP can be undertaken as either separate activities independently, or cumulatively as one process. Water companies could use it periodically for strategic assessment of general implications of environmental legislation or other strategic influences, and annually to identify and update site specific analysis of the impact of legislation or other strategic influences. The main circumstances for the use of the Hybrid-DSP would be:

Phase 1 use: To screen the strategic factors affecting the management of potable water supply

To assess new or existing legislation currently implemented or to be implemented

In response to specific incidents or identified strategic water sector changes

Phase 2 use: To screen and analyse the factors affecting site specific potable water management

For site specific assessment of the implications of the factors identified in Phase 1.

For assessment of the implications of the factors identified in Phase 1 on the management of a specific "pressure".

The component parts of the Hybrid-DSP can be used in their own right as individual stages for strategic context setting; understanding complex causal relationships; and modelling uncertainties. The application of the Hybrid-DSP should be considered as an iterative process, and should be actively reviewed and revised as the information and understanding of the problem domain progresses over time.

Participation

The Hybrid-DSP is to be used in an interactive and participative way through facilitated focus group meetings or workshops. A range of water company representatives including water managers representing different parts of the business in workshops/ focus groups during the generic assessment phase 1, and subsequently with location specific water company representatives (e.g. from WTW/ WWTW) as well as potential local influential stakeholders for the site specific phase 2. Water company representatives would ideally include informants from: asset management, water resources, environmental regulation and water services.

Effectively this approach incorporates both a "top down" and "bottom up" perspective of the problem domain which are then combined with a detailed causal assessment to identify strategic implications.

The use of a Microsoft Excel 2010® "Workbook", would provide a focus for the facilitated activities, which can be populated for each of the stages of the Hybrid-DSP. The workbook can therefore be used in strategic planning workshops within water companies, as well as site specific planning workshops, with water company representatives from different departments.

Through the participatory approach organisational knowledge and capacity will be generated to more effectively manage potable water resources.

Resources required

The implementation of the Hybrid-DSP, requires the initiation of a cultural change in the way decisions and information is managed. The focus on the whole potable water supply chain, including the changes at the catchment level is required. Therefore expertise and data regarding the management of the wider catchment as well as abstraction and treatment level specific data is required.

The resources to implement the Hybrid-DSP include people within the water company and where appropriate from external organisations. The knowledge base required includes:

- Water resources management
- Asset investment
- Environmental regulation
- Catchment management (including activities taking place across the different catchments)
- Public relations (for any specific facilitated workshops involving external organisations or the general public).
- Probabilistic modelling (for the BN software)

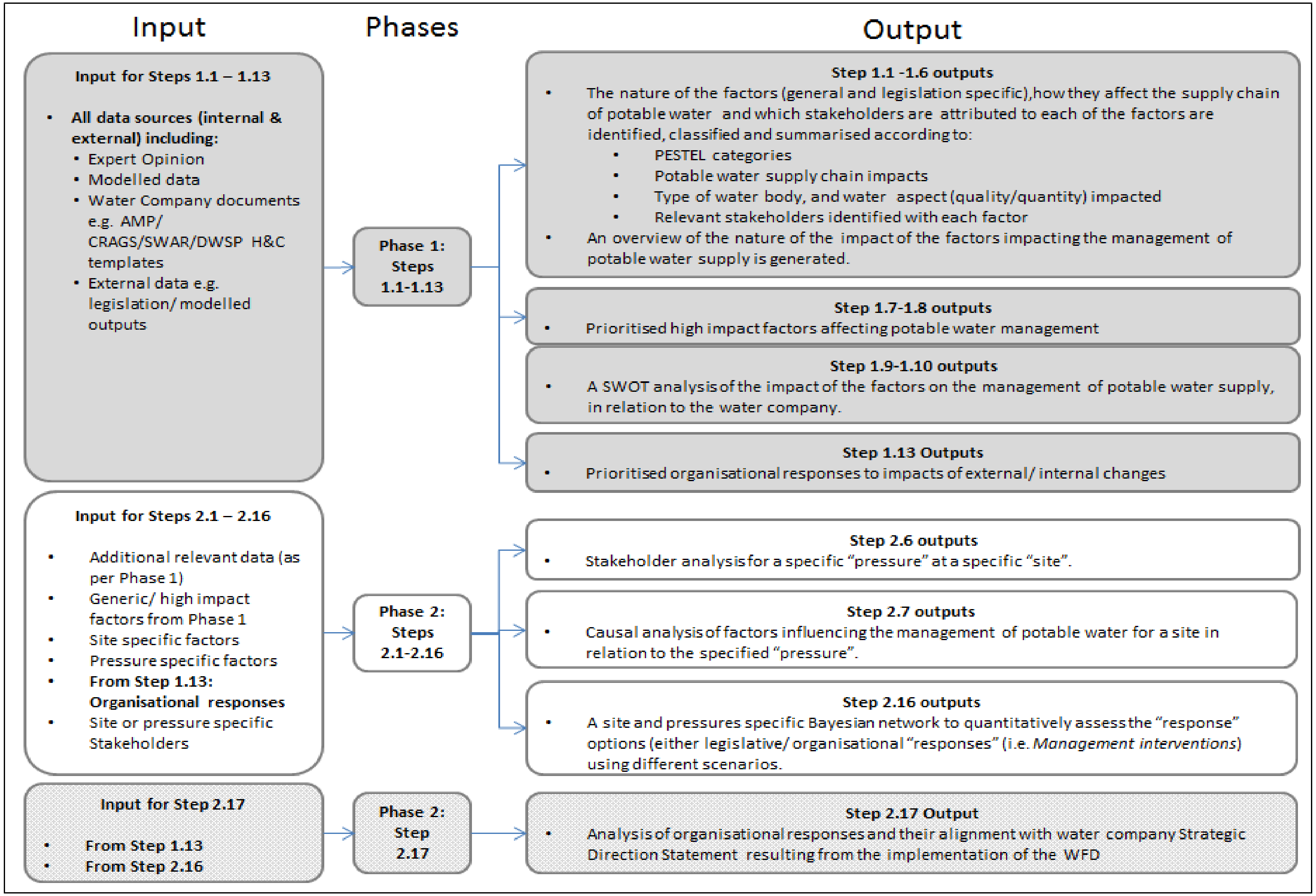
Data sources are from multiple sources including modelled data output, legislative documents, technical reports, site specific observations and knowledge, expert opinion. Specifically for the WFD, the UK River Basin Management Plans provide the information regarding the management intervention options to be implemented for specific “pressures” affecting water resources management.

Software requirements include Bayesian network software (e.g. Hugin A/S Expert) which would involve the purchase of the software, the licence and the training of its use by one or more members of the organisation. Consideration of the company wide installation is not recommended for the Bayesian network software, although potential future development may require organisational use of the software. Therefore the operation of the software using a standalone computer is recommended.

A Microsoft Excel ® spreadsheet “Workbook” acting as both a central database within which data can be stored, used as an evidence trail for audit purposes, and analysed to provide data for analysis using Bayesian network software, is recommended. The input of data generally follows each “row” in the spreadsheet, to allow categorisation and subsequent analysis. Within the “workbook” an electronic version of the specific data analysis can be incorporated (e.g. 'stakeholder grid', 'DPSIR grid’).

Outputs from the application of the Hybrid-DSP

The outputs from the Hybrid-DSP are presented in App Figure 2.



App Figure 2:Overview of the inputs and outputs from the Hybrid-DSP

Glossary

App Table 11: Glossary for Hybrid-DSP

Term	Definition	Step
Political	Highlights the role of governments: e.g. government stability/ taxation policy /foreign trade regulations/ social welfare policies (Johnson *et al.*, 2008)	Step 1.3
Economic	Mainly concerned with macro-economic factors: e.g. business cycles/ GNP trends/ interest rates/ money supply/ inflation/ unemployment/ disposable income (Johnson *et al.*, 2008)	Step 1.3
Social	Changes in cultures and demographics: e.g. population demographics/ income distribution/ social mobility/ lifestyle changes/ attitudes to work and leisure/ consumerism/ levels of education (Johnson *et al.*, 2008)	Step 1.3
Technical	The changes in technological developments: e.g. government spending on research/ government and industry focus on technological effort/ new discoveries and developments/ speed of technology transfer/ rates of obsolescence (Johnson *et al.*, 2008)	Step 1.3
Environmental	Specifically related to `green` issues: e.g. environmental protection laws/ pollution and waste disposal/ energy consumption (Johnson *et al.*, 2008)	Step 1.3
Legal	Legislative constraints or changes: e.g. monopolies legislation/ employment law/ health and safety/ product safety (Johnson *et al.*, 2008)	Step 1.3
Management of system	Management activities which impact on the potable water supply chain (including EU & National)	Step 1.4
Catchment	The wider catchment around a water abstraction point	Step 1.4
Abstraction	Point where water for potable consumption is abstracted	Step 1.4
Treatment	Treatment process for potable water supply	Step 1.4
Supply	Water distribution system and supply into customers taps	Step 1.4
SW	Surface water (e.g. rivers)	Step 1.5
GW	Groundwater	Step 1.5
AWB/ HMWB	Artificial Water Body (e.g. Lakes)/ Heavily Modified Water Body (e.g. Canals)	Step 1.5
Quality	Quality of water in the environment	Step 1.5
Quantity	Quantity of water in the environment	Step 1.5
Strengths	Internal organisational strengths in relation to the opportunities and threats posed by the changes in the external environment.	Step 1.9
Weaknesses	Internal organisational weaknesses in relation to the opportunities and threats posed by the changes in the external environment.	Step 1.9
Opportunities	External opportunities presented to the organisation as a result of changes in the external factors influencing the business environment	Step 1.9
Threats	External threats presented to the organisation as a result of the changes in the external factors influencing the business environment.	Step 1.9
Human (resources)	These include skills and know-how, communication and collaboration, and motivation. (Grant, 2005)	Step 1.11
Intangible (resources)	These include technology, reputation and culture. (Grant, 2005)	Step 1.11

Term	Definition	Step
Tangible (resources)	These include financial and physical resources. (Grant, 2005)	Step 1.11
Organisational Response	An ‘organisational response’ is a management intervention on behalf of the water company to address any potential improvements in resources or capabilities in response to the opportunities or threats identified	Step 1.12
Site	Site selected for investigation by the water company, based on sites at risk, or requiring further investigation as to the impact of a pressure at a site and surrounding catchment (source protection zone).	Step 2.1
Pressure	Pressure selected based on the identified pressures by the water company or from the RBMP for the management of potable water sources and supply.	Step 2.1
Impact on PW mgt (at site)	A qualitative assessment of the effect of the identified factor (e.g. treatment technology) on the management of potable water at the identified site (e.g. Barrow WTW).	Step 2.4
Impact on management of pressure (nitrate in catchment)	A qualitative assessment of the effect of the identified factor (e.g. NVZ) on the management of the identified pressure (e.g. nitrate) within the identified catchment (e.g. Barrow Source Protection Zone) around the potable water source (e.g. Barrow Borehole).	Step 2.4
Driving Force	An anthropogenic activity that may have an environmental effect (e.g. agriculture, industry) (EC, 2003).	Step 2.5
Pressure	The direct effect of the driver (for example, an effect that causes a change in flow or a change in the water chemistry) (EC, 2003).	Step 2.5
State	The condition of the water body resulting from both natural and anthropogenic factors (i.e. physical, chemical and biological characteristics) (EC, 2003).	Step 2.5
Impact	The environmental effect of the pressure (e.g. fish killed, ecosystem modified) [Within this research, the impact on the potable water supply system at the treatment and supply level, as well as the level of the management of the organisation, is used to understand the full impact of pressures and responses on the system.] (EC, 2003).	Step 2.5
Response	The measures taken to improve the state of the water body (e.g. restricting abstraction, limiting point source discharges, developing best practice guidance for agriculture) [Within this research the response from the water company perspective, as well as existing interventions are considered separately, to understand the cumulative impact, and identify areas where additional or reduced responses (interventions) are required.] (EC, 2003).	Step 2.5
Key players	Key stakeholders with both high interest and influence, with which close relationships would be of benefit	Step 2.6
Context Setters	Stakeholder with a high influence but limited interest. Therefore close relationships should be developed, to monitor and manage the potential risk they present.	Step 2.6
Subjects	Stakeholders who are supportive although lack the influential power needed to create change. Potential for collaborations of different 'subjects' may occur, which may result in greater influence.	Step 2.6
Crowd	Stakeholders with limited interest or influential power, and therefore do not need to be further engaged with.	Step 2.6
Supportive	Stakeholders show positive support for the management of the identified pressure on the potable water source.	Step 2.6
Neutral	Stakeholders do not show a preference either way.	Step 2.6

Term	**Definition**	**Step**
Unsupportive	Stakeholders show negative support for the management of the identified pressure on the potable water source.	Step 2.6
Reliability	Based on Ofwat guidance for June Return (2010) this band ranges from A to D. The classification of this banding can be identified in the tables provided to the right of this column.	Step 2.10
Accuracy	Based on Ofwat guidance for June Return (2010) this band ranges from 1 to 6 including X. The classification of this banding can be identified in the tables provided to the right of this column.	Step 2.10
Variable	Once all the ‘factors’ from the previous steps have been characterised, analysed and prioritised, they become known as variables to be included within the construction of the BN. *(The types of variables are defined below).*	Step 2.11
Background variable	A type of information variable: for solving a problem (represented by one or more problem variables). This is generally information already available before the problem occurred which influences the problem and symptom variables. These are normally the 'root' variables in a network (Kjaerulff and Madsen, 2008)	Step 2.11
Problem variable	These are the variables of interest - of which the posterior probability is the purpose of the construction of the BN. The values of the problem variables cannot be observed. These are also known as \`hypothesis variables\` and can be related to; diagnoses, classifications, predictions, decisions which are to be made (Kjaerulff and Madsen, 2008).	Step 2.11
Mediating variable	The variables are unobservable, and are primarily used to ensure correct conditional dependence or independence properties in the network. The parents of mediating variables are normally problem or background variables, with symptom variables as children (Kjaerulff and Madsen, 2008).	Step 2.11
Symptom variable	Symptom information can be observed, as a consequence of the presence of a problem, therefore is available after the occurrence of a problem. (*Note: problem variables have causal influences on symptoms variables*). Both problem and background variables are parents of symptom variables (Kjaerulff and Madsen, 2008).	Step 2.11
State (of a variable)	Each variable within the BN has a set of states in which the variable can be represented.(e.g. high, medium, low; <45 mg/l or > 45mg/l)	Step 2.13
Conditional probability table (CPT)	A table of probabilities to characterise the relationships between the variables within the network.	Step 2.15
Value of Information (VoI) analysis	An analysis conducted within BN software to assess where the greatest uncertainty is between variables within the network, and hence allows for the targeted allocation of resources to reduce the uncertainty in the network (Kjaerulff and Madsen, 2008).	Step 2.16

Implementation Steps – Overview

Phase 1: Generic assessment

Characterisation and identification of influential factors for potable water management (General and WFD specific factors)

Step 1.1

Identify general industry factors which influence the potable water supply chain (Q: What factors (external and internal) influence the management of the potable water supply chain? - use PESTEL framework as a guide) [Add a description of the factor and individual reference numbers for each factor].

Step 1.2

In addition to general factors, identify legislative factors (e.g. WFD) which influence the potable water supply chain. (Q: What specific legislative factors (e.g. WFD) impact the management of the potable water supply chain?). [Add a description of the factor and individual reference numbers for each factor].

Step 1.3

Characterise the nature of the factors impacting on the potable water supply chain as PESTE or L (definitions in App Table 11). (Q: In what way do the identified factors affect the potable water supply chain?)

Step 1.4

Identify for each factor how it would impact the management of the potable water supply chain, using the definitions of the systems levels provided in App Table 11. (Q: Which part of the potable water supply chain does the identified factor target?)

Step 1.5

For each factor, identify the type and aspect of water body affected, using the definitions as provided in App Table 11. (Q: Which type of water body and in what way (quality or quantity) does the factor affect?

Step 1.6

Identify the key stakeholders associated with the variable (Q: Which stakeholders influence the effect of the factor?).

Step 1.7

Identify the impact of the "factor" on the management of potable water, and therefore allow for a prioritised list to be generated.(Q: What is the impact on potable water management? – High, Medium or Low).

Step 1.8

Select only those factors with a high effect on the management of potable water to be considered for further more detailed analysis in the subsequent steps.

Organisational strategic analysis (Steps 1.9 – 1.13)

Step 1.9

Identify the opportunities and threats posed by the prioritised factors in Step 1.8, using the definitions in App Table 11 as a guide. (Q: What are the opportunities and threats posed by the identified factor?)

Step 1.10

Identify the organisational strengths and weaknesses in relation to the potential opportunities and threats, add a description to the main worksheet. (Q: What are the organisational strengths and weaknesses in response to the opportunities and threats posed by the factor?).

Step 1.11

Identify whether further organisational resources and capabilities (e.g. Human/ Tangible/ Intangible) are required and in what way they should be developed in order to respond to the external changes. Use the definitions in App Table 11 as a guide. (Q: What are the resources and capabilities to be further considered for development within the organisation to improve the effectiveness and efficiency of the organisation?).

Step 1.11.1:

Summarise the type of the resource and capability required and illustrate through the production of a graph for each of the types of factor (e.g. general or WFD specific).

Step 1.12

Identify potential strategic organisational responses to be considered, and list across the heading row. Cross reference each proposed response to each of the factors assessed.

Step 1.13

Conduct a resource and capability assessment for strategic organisational investment identification (following Steps 1.13.1 to 1.13.5)

Phase 2: Site specific assessment

Causal analysis (Variable identification for specific pressure and site Step 2.1-2.3)

Step 2.1

Identify specific pressure/s and site (as defined in App Table 11) for strategic investment implications to be considered to deliver potable water supply (using the PESTEL framework as a guide), and enter in the workbook.

Step 2.2

Identify general site specific factors which influence potable water management, in addition to those affecting potable water management identified in Phase . (following Step 2.2.1 – 2.2.3).

Step 2.3

Categorise all the site specific factors by repeating steps 1.3 to 1.8 of Phase 1.(*Follow definitions for Phase 1 Steps 1.3 to 1.8).*

Causal analysis: factor prioritisation and DPSIR preparation (Step 2.4 – 2.5)

Step 2.4

At this point, the factors from Phase 1 are included alongside the factors identified from Phase 2 for the site specific analysis for the pressure identified impacting the management of potable water

Step 2.5

Select the high priority factors from Step 2.4 and classify the selected variables as DPSI or R. The factors identified form the basis of the causal grid developed in Step 2.7.

Stakeholder analysis (Step 2.6)

Step 2.6

Using the prioritised factors identified in Step 2.5, identify the associated stakeholders for these factors and complete a stakeholder analysis: Select the stakeholders associated with the management of the pressure at the specific site identified. Identify the level of interest and influence (between 1 =low, and 10= high) each of the stakeholders has, together with their perceived attitude towards the management of the pressure, this can be identified within a workshop by individuals, or through a survey of water managers (following steps 2.6.1 – 2.6.7). These stakeholders can therefore be considered in association with the factors within the causal analysis in Step 2.7.

Causal analysis: DPSIR grid (Step 2.7)

Step 2.7

Complete a Causal Analysis: Use the selected high impact/ effect factors identified for the specific site and pressure (from Step 2.4) and insert into the causal analysis grid (DPSIR grid in the Microsoft Excel 2010® workbook) including the organisational response options identified (from both Phase 1 (step 1.13) and Phase 2 (step 2.2.3, and Step 2.6).

BN development (variable identification) (Steps 2.8 – 2.15)

Step 2.8

Using the DPSIR analysis as a reference identify the system boundaries and "factors" to be taken forward for analysis using Bayesian networks (e.g. combining factors, elimination of factors, or any further additional factors). Select these within the main Microsoft Excel 2010® Workbook, through liaison with water managers through a workshop or focus group.

Step 2.9

Identify data sources for each selected factor (variable).

Step 2.10

Identify data confidence (related to reliability and accuracy) for each variable. Hence the data is classified according to the Ofwat criteria for the June Return 2010. (see App Table 11).

Step 2.11

Categorise the variables according to Kjaerulff and Madsen (2008) variable types, using definitions in App Table 11 and as a guide.

Step 2.12

Identify an abbreviated name to reference the variable within the network (using an underscore (_) instead of a space e.g. groundwater quality = GW_Quality)

Step 2.13

Identify the potential states of variables (using analysis of data when available or expert opinion)

Step 2.14

Use variable data for the construction of the Bayesian Network within the Bayesian Network Software (e.g. Hugin Expert A/S).

Step 2.15

Identify conditional probabilities (via data sources e.g. expert opinion or deterministic modelled data when available) for variables, and verify model through a workshop of water managers or experts (hence peer review due to limited data for predictions of the future for some variables e.g. impact of legislation implementation).

Scenario analysis (Step 2.16)

Step 2.16

Identify scenarios with water manager for the network based on variables considered to be more certain. Conduct scenario analysis through the Bayesian network to identify the implications of a change in the problem variables, or the type or level of organisational management interventions to manage the selected pressure.

Strategic options analysis (Step 2.17)

Step 2.17

Identify strategic options through evaluation of organisational responses identified in Step 1.13 and investment options for the identified site specific scenario's from Step 2.16 against the organisational strategic priorities as identified in the strategic direction statement (following Steps 2.17.1 – 2.17.10).

End of Phase 2

Implementation steps – detailed process

To facilitate the management and analysis of the data generated through the Hybrid-DSP, use of the pre-formatted Microsoft Excel® "workbook" is recommended.

Phase 1: Generic assessment

Steps 1.1- 1.8: Characterisation and identification of influential factors for potable water management (General and WFD specific factors)

Purpose: To systematically characterise identified factors which influence potable water management. Through undertaking steps 1.1-1.8 in a participatory way (e.g. workshops/ focus groups), organisational understanding of the nature of the problem will be generated. Therefore a more informed position can be taken for the identification of organisational responses and hence strategic investment prioritisation for potable water management.

Step 1.1

Identify general industry factors which influence the potable water supply chain (Q: What factors (external and internal) influence the management of the potable water supply chain? - use PESTEL framework as a guide) [Add a description of the factor and individual reference numbers for each factor].

Step 1.2

In addition to general factors, identify legislative factors (e.g. WFD) which influence the potable water supply chain. (Q: What specific legislative factors (e.g. WFD) impact the management of the potable water supply chain?). [Add a description of the factor and individual reference numbers for each factor].

Step 1.3

Characterise the nature of the factors impacting on the potable water supply chain as PESTE or L (definitions in App Table 12). (Q: In what way do the identified factors affect the potable water supply chain?)

App Table 12: Definition of PESTEL factors (Johnson and Scholes, 2002; Johnson *et al.*, 2008)

PESTEL factor	Definition
Political	Highlights the role of governments: e.g. Government Stability/ Taxation Policy /Foreign trade regulations/ Social Welfare policies.
Economic	Mainly concerned with macro-economic factors: e.g. Business cycles/ GNP trends/ Interest rates/ Money Supply/ Inflation/ Unemployment/ Disposable income

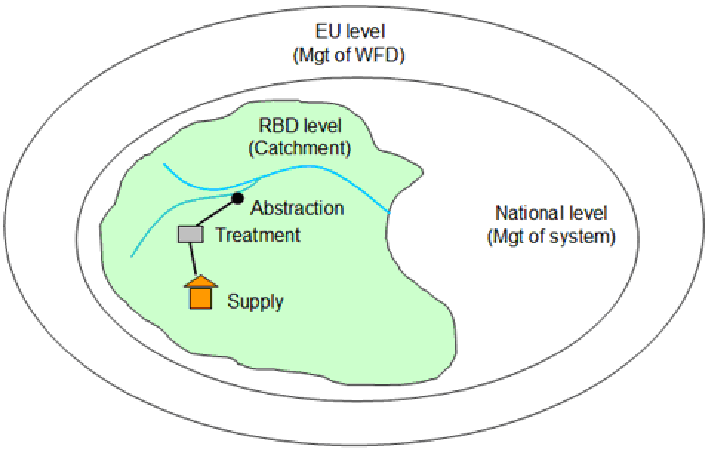
PESTEL factor	Definition
Social	Changes in cultures and demographics: e.g. Population demographics/ Income distribution/ Social mobility/ lifestyle changes/ attitudes to work and leisure/ consumerism/ levels of education.
Technological	The changes in technological developments: e.g. Government spending on research/ Government and industry focus on technological effort/ new discoveries and developments/ speed of technology transfer/ rates of obsolescence
Environmental	Specifically related to `green` issues: e.g. Environmental protection laws/ pollution and waste disposal/ energy consumption
Legal/ Regulatory	Legislative constraints or changes: e.g. Monopolies legislation/ employment law/ health and safety/ product safety.

Step 1.4

Identify for each factor how it would impact the management of the potable water supply chain, using the definitions of the systems levels provided in App Table 13, and represented in App Figure 3. (Q: Which part of the potable water supply chain does the identified factor target?)

App Table 13: Potable water supply chain system classifications

System level	**Definition**
Management of system	management activities which impact on the potable water supply chain (including EU & National)
Catchment	the wider catchment around a water abstraction point
Abstraction	point where water for potable consumption is abstracted
Treatment	treatment process for potable water supply
Supply	water distribution system and supply into customers taps



App Figure 3: System levels used for the classification of the impact of the factor on the management of the potable water supply chain.

Therefore through the systems level analysis, the water manager can understand where within the supply chain the factors which impact the management of potable water supply are targeting. Hence resources can be targeted at the appropriate system level by the organisation.

Step 1.5

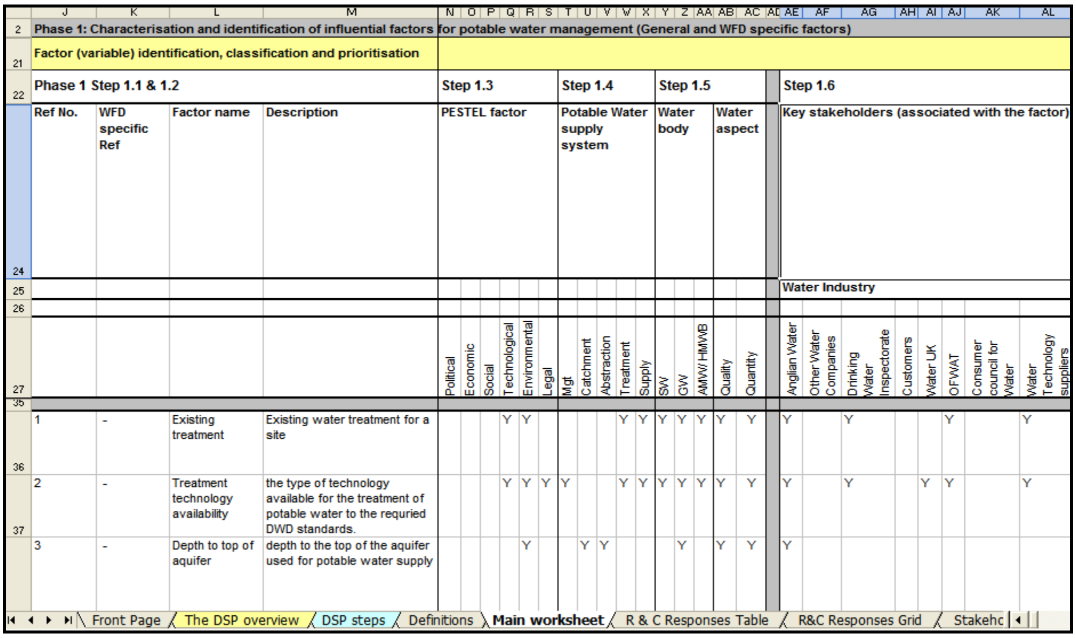
For each factor, identify the type and aspect of water body affected, using the definitions as provided in App Figure 15. (Q: Which type of water body and in what way (quality or quantity) does the factor affect?

App Table 14: Notation used for water bodies

Abbreviation	Definition
SW	Surface water (e.g. rivers)
GW	Groundwater
AMW/ HMWB	Artificial Modified Water Body (e.g. Lakes)/ Heavily Modified Water Body (e.g. Canals)
Quality	Quality of water in the environment
Quantity	Quantity of water in the environment

Step 1.6

Identify the key stakeholders associated with the variable (Q: Which stakeholders influence the effect of the factor?). App Figure 4 highlights an exert from the Microsoft Excel 2010® workbook as an example.



Phase 1: Characterisation and identification of influential factors for potable water management (General and WFD specific factors)

Factor (variable) identification, classification and prioritisation

Phase 1 Step 1.1 & 1.2				Step 1.3						Step 1.4					Step 1.5					Step 1.6							
Ref No.	WFD specific Ref	Factor name	Description	PESTEL factor						Potable Water supply system					Water body			Water aspect		Key stakeholders (associated with the factor)							
																				Water Industry							
				Political	Economic	Social	Technological	Environmental	Legal	Mgt	Catchment	Abstraction	Treatment	Supply	SW	GW	AMWW/ HMWB	Quality	Quantity	Anglian Water	Other Water Companies	Drinking Water Inspectorate	Customers	Water UK	OFWAT	Consumer council for Water	Water Technology suppliers
1	-	Existing treatment	Existing water treatment for a site				Y	Y					Y	Y	Y	Y	Y	Y	Y	Y		Y			Y		Y
2	-	Treatment technology availability	the type of technology available for the treatment of potable water to the requried DWD standards.				Y	Y	Y	Y			Y	Y	Y	Y	Y	Y	Y	Y		Y		Y	Y		Y
3	-	Depth to top of aquifer	depth to the top of the aquifer used for potable water supply					Y			Y	Y				Y		Y	Y	Y							

App Figure 4: The Hybrid-DSP process steps 1.1 to 1.6

Therefore all stakeholders for each factor are identified and the dominant stakeholders associated with the management of potable water are identified in relation to the factors identified.

Step 1.7

Identify the impact of the "factor" on the management of potable water, and therefore allow for a prioritised list to be generated.(Q: What is the impact on potable water management? – High, Medium or Low).

Step 1.8

Select only those factors with a high effect on the management of potable water to be considered for further more detailed analysis in the subsequent steps.

Steps 1.9 – 1.13: Organisational strategic analysis

Purpose: To understand what the position of the organisation is in relation to the changes in both the internal and external organisational environments, and to identify what additional resources and capabilities are required for the organisation to response to the changes.

Step 1.9

Identify the opportunities and threats posed by the prioritised factors in Step 1.8, using the definitions in App Table 15 as a guide. (Q: What are the opportunities and threats posed by the identified factor?)

App Table 15: SWOT definitions

Strengths	Internal organisational strengths in relation to the opportunities and threats posed by the changes in the external environment.
Weaknesses	Internal organisational weakness in relation to the opportunities and threats posed by the changes in the external environment.
Opportunities	External opportunities presented to the organisation as a result of changes in the external factors influencing the business environment
Threats	External threats presented to the organisation as a result of the changes in the external factors influencing the business environment.

Step 1.10

Identify the organisational strengths and weaknesses in relation to the potential opportunities and threats, add a description to the main worksheet. (Q: What are the organisational strengths and weaknesses in response to the opportunities and threats posed by the factor?).

Step 1.11

Identify whether further organisational resources and capabilities (e.g. Human/ Tangible/ Intangible) are required and in what way they should be developed in order to respond to the external changes. Use the definitions in App Table 16 as a guide. (Q: What are the resources and capabilities to be further considered for development within the organisation to improve the effectiveness and efficiency of the organisation?).

App Table 16: Resources and capability definition (Grant, 2005: 140)

Resources and capabilities	Relevant characteristics
Human	
Skills/ know-how	The education, training and experiences of employees determine the skills available to the firm.
Communication/ collaboration	The adaptability of employees contributes to the strategic flexibility of the firm. The social and collaborative skills of employees determine the capacity of the firm to transform human resources into organisational capabilities
Motivation	The commitment and loyalty of employees determine the capacity of the firm to attain and maintain competitive advantage
Intangible	
Technology	Intellectual property: patent portfolio, copyright, trade secrets. Resources for innovation: research facilities, technical, scientific employees.
Reputation	Reputation with customers through the ownership of brands and trademarks; established relationships with customers; the reputation of the firm's products and services for quality and reliability. The reputation of the company with the suppliers, government, and the community
Culture	Culture to support the development of resources and capabilities
Tangible	
Financial	The firms borrowing capacity and its internal funds generation determine its resilience and capacity for investment
Physical	Physical resources constrain the firms set of production possibilities and impact its cost position. Key characteristics include: the size, location, technical sophistication, and flexibility of plant and equipment/ location and alternative use for land and buildings/ reserves of raw materials.

Step 1.11.1: Summarise the type of the resource and capability required and illustrate through the production of a graph for each of the types of factor (e.g. general or WFD specific).

Phase 1: Characterisation and ident			Phase 1: Organisational strategic analysis					
Factor (variable) identification, clas			External variable analysis		Internal organisational analysis		Resource and capability requirements a	
Phase 1 Step 1.1 & 1.2			Step 1.9		Step 1.10		Step 1.11	
Ref No.	**WFD specific Ref**	**Factor name**	**Opportunities** (of factor/ variable)	**Threats** (of factor/ variable)	**Strengths** (of water company)	**Weaknesses** (of water company)	**Description of potential resource and capability required**	**Huma**
								Skills/ know-how
1	-	Existing treatment	understand the performance of existing treatment	poorly understood assets, would lead to inefficient operation and performance	internal operational management of existing assets	limited consideration of changes in the future operating environment as forecasts are	future modelling and understanding required of the nature of the changes in treatment requirements into the future.	Y
2	-	Treatment technology availability	development of further treatment technologies	unavailability of technology may present risk to PW DWD standards.	continuous development in technology through innovation team	not enough resources to increase development.	development of innovative treatment technological designs.	Y
3	-	Depth to top of aquifer	knowing the depth to top of aquifer would inform the potential risk of contamination of the GW source	unknown depth would not allow for informed judgement regarding potential susceptibility of aquifer to contamination	internal documentation regarding GW assets provides data regarding depths of aquifers.	limited dynamic understanding of the variation In the depth of the aquifer	further data monitoring as to the nature of the changes in the aquifer depth	

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App Figure 5: The Hybrid-DSP process steps 1.9 to 1.11

Phase 1: Characterisation and ident															
Factor (variable) identification, clas			Resource and capability requirements and classification										Response options to be further considered in Phase 2		
Phase 1 Step 1.1 & 1.2			Step 1.11										Step 1.12		
Ref No.	**WFD specific Ref**	**Factor name**	**Description of potential resource and capability required**	**Human**			**Tangible**		**Intangible**				Modelling of future water quality and quantity changes on requirements for water treatment	Further development of innovative treatment technologies	Research and investigation in aquifer characteristics and responses to pollution
													R1	**R2**	**R3**
				Skills/ know-how	communication/ collaboration	Motivation	Financial	Physical	Technology	Reputation	Culture				
1	-	Existing treatment	future modelling and understanding required of the nature of the changes in treatment requirements into the future.	Y	Y		Y		Y		Y		Y		
2	-	Treatment technology availability	development of innovative treatment technological designs.	Y	Y		Y	Y	Y		Y			Y	
3	-	Depth to top of aquifer	further data monitoring as to the nature of the changes in the aquifer depth		Y				Y						Y

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App Figure 6: The Hybrid-DSP process Step 1.11 and Step 1.12

Step 1.12

Identify potential strategic 'organisational responses' to be considered, and list across the heading row. Cross reference each proposed response to each of the factors assessed.

[NOTE: an 'organisational response' is a management intervention on behalf of the water company to address any potential improvements in resources or capabilities in response to the opportunities or threats identified].

Step 1.13

Conduct a resource and capability assessment for strategic organisational investment identification (following Steps 1.13.1 to 1.13.5)

Step 1.13.1 Copy all responses identified in Phase A Step 1.13 into the column within the resources and capability analysis table below.

Step 1.13.2 Grade each of the responses with regard to their strategic importance, and the relative strength of the organisation using the scale as indicated in App Table 17 and App Table 18.

App Table 17: Scale for strategic importance and relative organisational strength for 1.13.2

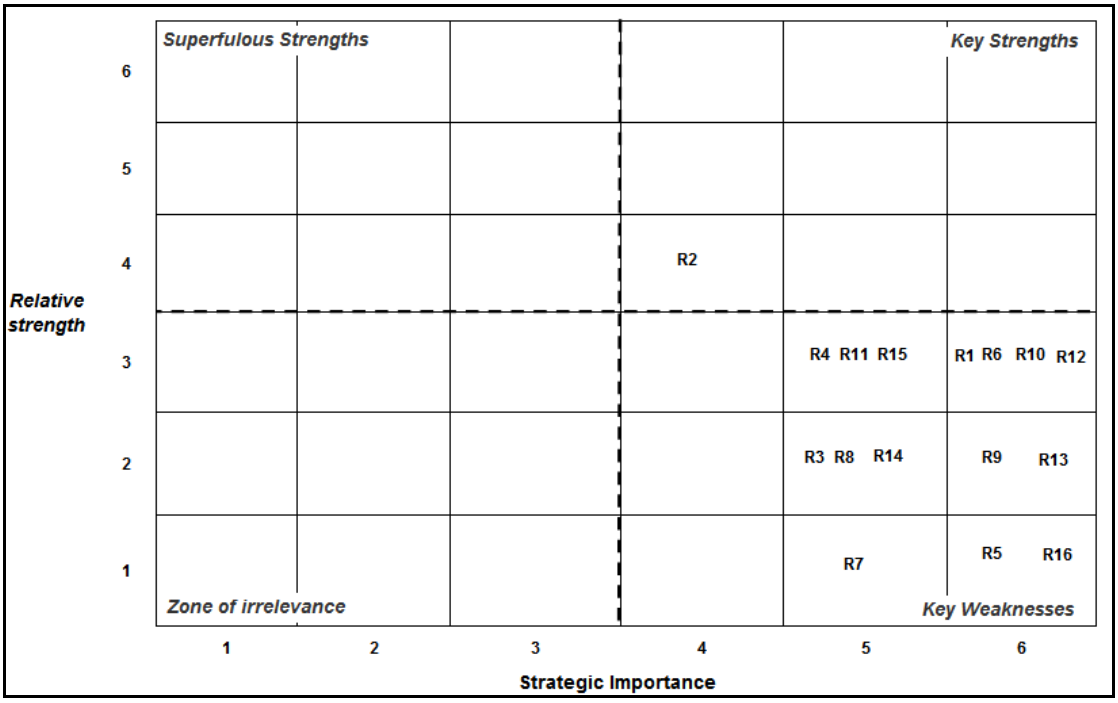
Strategic importance	**Scale**	***Relative organisational strength***	**Scale**
Extremely Important	**6**	extremely high	**6**
Very Important	**5**	very high	**5**
Important	**4**	high	**4**
moderately important	**3**	average	**3**
not very important	**2**	low	**2**
Not important	**1**	very low	**1**

App Table 18: Example of a resource and capability assessment of organisational responses (from Step 1.12)

Ref	***Resource and capability identified [d]***	***Strategic Importance (1-6)[b]***	***Relative strength (1-6)[c]***
R1	Modelling of future water quality and quantity changes on requirements for water treatment	6	3
R2	Further development of innovative treatment technologies	4	4
R3	Research and investigation in aquifer characteristics and responses to pollution	5	2
R4	Increased monitoring of raw water sources (both parameters and frequency)	5	3

[a] the ratings of the strategic importance and relevant strengths are based on the authors subjective judgement.
[b] the strategic importance scale ranges from 1 to 6 (1 = not important, 2 = not very important, 3 = moderately important, 4 = important, 5 = very important, 6 = extremely important.)
[c] the relative strength scale ranges from 1 to 6 (1 = very low, 2 = low, 3= average, 4= high, 5 = very high, 6 = extremely high)
[d] the resources and capabilities are identified from the Phase 1 assessment

Step 1.13.3 Position each of the reference codes for the resources and capabilities on the grid as in App Figure 7.



App Figure 7: Example resources and capability strategic assessment grid.

Step 1.13.4 Identify the key resources and capabilities to be further considered for strategic investment options. (hence key weaknesses)

Step 1.13.5 Select and paste the identified strategic options for investment within the strategic options assessment spreadsheet (within the Microsoft Excel 2010® workbook) (Step 2.17)

Output of Phase 1

Through the analysis of the factors identified through Phase 1, an indication of what factors affect the management of potable water supply, in what way, who may be involved, and what organisational responses may need to be considered to address the impact the identified factors may have on the management of potable water. This assessment represents an holistic assessment of the factors affecting the management of the potable water supply chain , and therefore provides a basis from which further site specific analysis can be conducted, as indicated within Phase 2.

End of Phase 1

Phase 2: Site specific assessment

Step 2.1-2.3: Causal analysis (Variable identification for specific pressure and site)

Purpose: To understand the relationships between factors (and associated stakeholders), to ultimately determine the prioritisation of stakeholder engagement for a specific site/ pressure. (Hence the site/pressure specific stakeholders identified may also be able to provide sources of data for further use to inform potable water management e.g. farmers management plans and hence pesticide/ nitrogen applications within catchments.)

In Step 2.1 the selection of the site is determined by the water company, where a site of interest can be considered as one in which a high risk of contamination is already present, no risk currently present or for other strategic consideration as determined by the water company. The pressure selected is identified as nitrate, as this has and continues to present the greatest risk to the management of potable water resources across the Anglian region.

In Step 2.2 the identification and characterisation of the factors related specifically to the management of potable water and the selected pressure (nitrate) at the specific site are considered. The incorporation of the strategic responses as identified from Phase 1 are also listed to allow for incorporation as variables to be considered in the development of the Bayesian network. Step 2.3 follows the characterisation process as per Step 1.1 to 1.8 in the generic phase 1, with ultimately the prioritisation of the variables considered for further analysis in Step 2.4.

Step 2.1

Identify specific pressure/s and site (as defined in App Table 19) for strategic investment implications to be considered to deliver potable water supply (using the PESTEL framework as a guide), and enter in the workbook (App Figure 8).

App Table 19: Definition of 'site' and 'pressure' used in the Hybrid-DSP

Term	**Definition**
Site	Site selected from Anglian Water based on sites at risk, or requiring further investigation as to the impact of a pressure at a site and surrounding catchment (source protection zone).
Pressure	Pressure selected based on the identified pressures from either Anglian Water or from the RBMP for the management of potable water sources and supply

Step 2.2

Identify general site specific factors which influence potable water management, in addition to those affecting potable water management identified in Phase 1, and identify within the workbook under the column headings as listed in App Table 20, as per App Figure 8.

Step 2.2.1

Identify pressure specific characteristics which may influence the management of the potable water supply

Step 2.2.2

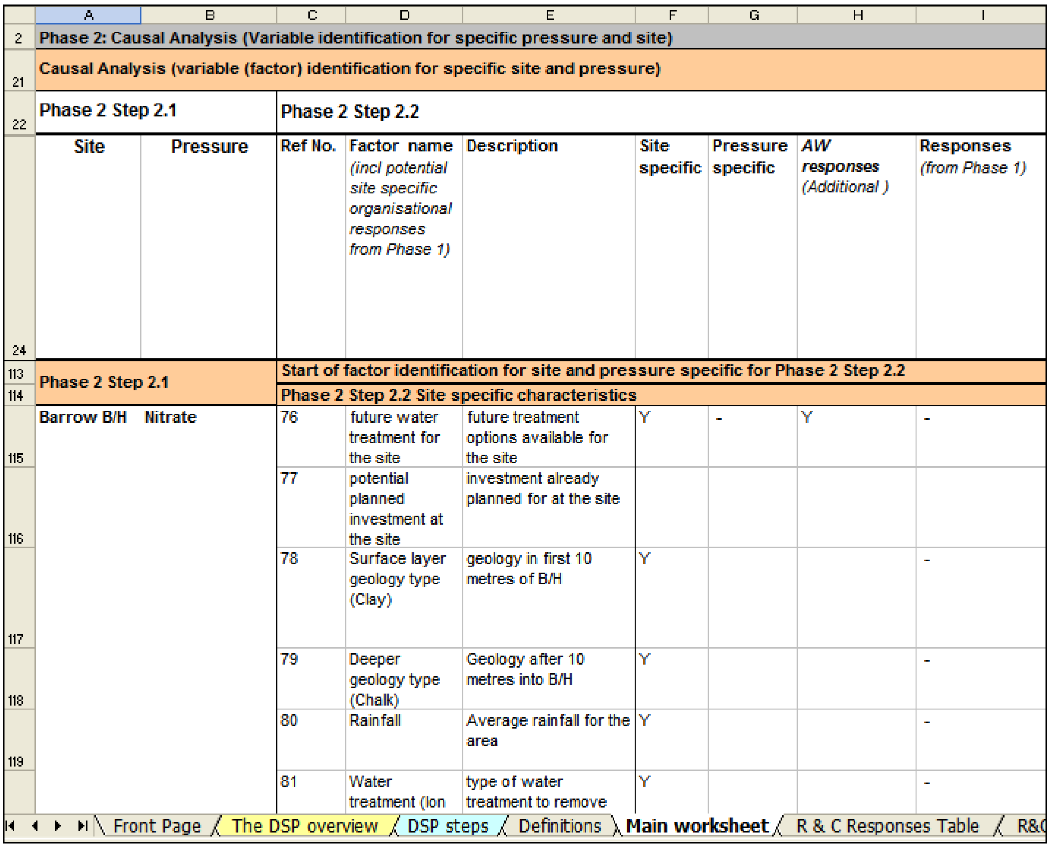
List the organisational responses identified in Phase 1 (step 1.13) for consideration as potential site specific responses for the pressure. [note: a SWOT analysis is not considered at this stage, as main issues were covered in Phase 1, therefore only a review of those responses identified is conducted, with additional site specific responses identified. The conduct of a full SWOT analysis at a site specific level could be further applied to provide for a more thorough review].

Step 2.2.3

Identify any specific organisational responses to address the specific pressure at the selected site, and add to the list of factors to be analysed for the site/pressure in subsequent steps.

App Table 20: Colum heading definitions for 'workbook'.

Heading	**Definition**
Ref No.	Numerical reference number used to track the factor.
Factor name *(incl. potential site specific organisational responses from Phase 1)*	Name of additional factors identified in association with the specific pressure (e.g. nitrate), or the catchment/ site (e.g. Barrow catchment), which includes key site specific factors identified in Phase 1.
Description	Description of the factor identified.
Site specific	designation as site specific factor
Pressure specific	designation as pressure specific factor
AW responses *(Additional)*	Designation of factors as additional response options to be considered by water company,
Responses *(from Phase 1)*	Designation as response identified in Phase 1.



Phase 2: Causal Analysis (Variable identification for specific pressure and site)								
Causal Analysis (variable (factor) identification for specific site and pressure)								
Phase 2 Step 2.1		Phase 2 Step 2.2						
Site	Pressure	Ref No.	Factor name *(incl potential site specific organisational responses from Phase 1)*	Description	Site specific	Pressure specific	***AW responses*** *(Additional)*	Responses *(from Phase 1)*
Phase 2 Step 2.1		Start of factor identification for site and pressure specific for Phase 2 Step 2.2						
		Phase 2 Step 2.2 Site specific characteristics						
Barrow B/H	Nitrate	76	future water treatment for the site	future treatment options available for the site	Y	-	Y	-
		77	potential planned investment at the site	investment already planned for at the site				
		78	Surface layer geology type (Clay)	geology in first 10 metres of B/H	Y			-
		79	Deeper geology type (Chalk)	Geology after 10 metres into B/H	Y			-
		80	Rainfall	Average rainfall for the area	Y			-
		81	Water treatment (Ion	type of water treatment to remove	Y			-

App Figure 8: The Hybrid-DSP process Step 2.1 and 2.2

Step 2.3

Categorise all the site specific factors by repeating steps 1.3 to 1.8 of Phase 1.(*Follow definitions for Phase 1 Steps 1.3 to 1.8)* as per App Table 11, and shown in App Figure 9. Through the characterisation of the factors, a greater understanding of the nature of the factors affecting potable water management will be obtained, and hence inform the management options to be considered for the specific pressure and site.

or) identification for specific site and pressu																												
Phase 2 Step 2.2			Step 1.3						Step 1.4					Step 1.5					Step 1.6								
Ref No.	Factor name *(incl potential site specific organisational responses from Phase 1)*	Description	PESTEL factor						Potable Water supply system					Water body			Water aspect		Key stakeholders (associated with the factor)								
																			Water Industry								
			Political	Economic	Social	Technological	Environmental	Legal	Mgt	Catchment	Abstraction	Treatment	Supply	SW	GW	AW/ HMWB	Quality	Quantity	Anglian	Other Water Companies	Drinking Water Inspectorate	Customers	Water UK	OFWAT	Consumer council for Water	Water Technology suppliers	Industry (Business customers)
Phase 2 Step 2.2 Site specific characteristics			Phase 2 Step 2.3																								
76	future water treatment for the site	future treatment options available for the site	Y	Y		Y			Y			Y					Y	Y	Y		Y	Y	Y	Y	Y	Y	
77	potential planned investment at the site	investment already planned for at the site	Y	Y		Y			Y			Y					Y	Y	Y		Y			Y	Y	Y	
78	Surface layer geology type (Clay)	geology in first 10 metres of B/H					Y			Y	Y				Y		Y	Y	Y							Y	
79	Deeper geology type (Chalk)	Geology after 10 metres into B/H					Y			Y	Y								Y							Y	

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App Figure 9: The Hybrid-DSP Phase 2 Step 2.3

Step 2.4 – 2.5:Causal analysis: factor prioritisation and DPSIR preparation

Purpose: To understand how factors are causally related, and hence identify how management interventions (responses) can be used to influence the variables of interest. Therefore promote organisational learning of the interactions of the broader system governing water resources management.

In step 2.4 the effect the factors have on the management of the potable water supply and the effect on the management of the selected pressure (nitrate) are considered. These are qualitatively determined by the researcher based on informed judgement as high, medium or low. The factors which have a high effect are further considered within the causal analysis assessment in Step 2.5. The factors are determined to be driving forces, pressures, state of the environment, state of the water resource, impact on the treatment, supply and management of potable water and the responses to manage the potable water or the pressure (nitrate). These responses are considered to be either the existing responses, WFD response or further responses required by Anglian Water. These factors can be determined by water managers based on informed judgement or specific plans or programmes.

Step 2.4

At this point, the factors from Phase 1 are included alongside the factors identified from Phase 2 for the site specific analysis for the pressure identified impacting the management of potable water. [*Note: Even though the factors from Phase 1 were prioritised according to H,M and L in*

Step 1.8, the factors are reassessed in relation to the site specific relevance of the factor, and hence only take forward the factors which are relevant for the specific site and/or pressure]. All the factors are assessed according to their impact on the management of potable water at the site or on the management of the pressure as High, Medium, or Low. The definition of these categories is provided in App Table 21.

App Table 21: Definition of impact category for site and pressure specific analysis of factors.

Impact category	**Definition**
Impact on PW mgt (at site)	A qualitative assessment of the effect of the identified factor (e.g. treatment technology) on the management of potable water at the identified site (e.g. Barrow WTW).
Impact on management of pressure (nitrate in catchment)	A qualitative assessment of the effect of the identified factor (e.g. NVZ) on the management of the identified pressure (e.g. nitrate) within the identified catchment (e.g. Barrow Source Protection Zone) around the potable water source (e.g. Barrow Borehole).

Therefore a list of prioritised factors is generated to be taken forward for causal analysis in Step 2.5 and 2.7.

Step 2.5

Select the high priority factors from Step 2.4 and classify the selected variables as DPSI or R, using the definitions in App Table 22 as a guide.

App Table 22: The DPSIR framework as used in the pressures and impacts analysis (EC, 2003a).

DPSIR factor	**Definition**
Driver	an anthropogenic activity that may have an environmental effect (e.g. agriculture, industry)
Pressure	the direct effect of the driver (for example, an effect that causes a change in flow or a change in the water chemistry)
State	the condition of the water body resulting from both natural and anthropogenic factors (i.e. physical, chemical and biological characteristics)
Impact	the environmental effect of the pressure (e.g. fish killed, ecosystem modified) *[Within this research, the impact on the potable water supply system at the treatment and supply level, as well as the level of the management of the organisation, is used to understand the full impact of pressures and responses on the system.]*
Response	the measures taken to improve the state of the water body (e.g. restricting abstraction, limiting point source discharges, developing best practice Guidance for agriculture) [*Within this research the response from the water company perspective, as well as existing interventions are considered separately, to understand the cumulative impact, and identify areas where further or less response (interventions) are required.]*

The factors identified form the basis of the causal grid developed in Step 2.7.

	C	D	E	CS	CT	CY	CZ	DA	DB	DC	DD	DE	DF	DG
21	or) identification for specific site and pressu			Prioritisation		DPSIR classification								
22	Phase 2 Step 2.2			Phase 2 Step 2.4		Phase 2 Step 2.5								
24	Ref No.	Factor name *(incl potential site specific organisational responses from Phase 1)*	Description	Effect on PW mgt (at site)	Effect on management of pressure (nitrate in catchment)	Driving Force	Pressure	State of environment	State of water	Impact on treatment	Impact on supply	Impact on management of organisation	Response (general and WFD specific)	Response (through AW)
114	Phase 2 Step 2.2 Site specific characteristics													
115	76	future water treatment for the site	future treatment options available for the site	H	H	N	N	N	N	N	N	N	N	Y
116	77	potential planned investment at the site	investment already planned for at the site	H	M	N	N	N	N	N	N	N	N	Y
117	78	Surface layer geology type (Clay)	geology in first 10 metres of B/H	H	H	N	N	Y	N	N	N	N	N	N
118	79	Deeper geology type (Chalk)	Geology after 10 metres into B/H	H	H	N	N	Y	N	N	N	N	N	N
119	80	Rainfall	Average rainfall for the area	M	M	N	N	Y	N	N	N	N	N	N
120	81	Water treatment (Ion Exchange)	type of water treatment to remove the specific pressure	H	H	N	N	N	N	N	N	N	N	Y
	82	Cost of	cost of water	H	H	N	N	N	N	Y	N	N	N	N

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App Figure 10: Example of the Hybrid-DSP workbook Step 2.4-2.5.

Step 2.6: Stakeholder analysis

Purpose: To understand which stakeholders are influential in the management of the problem domain under investigation and hence which stakeholders to develop strategic relationships with to inform the management of potable water resources.

Step 2.6

Using the prioritised factors identified in Step 2.5, identify the associated stakeholders for these factors and complete a stakeholder analysis: Select the stakeholders associated with the management of the pressure at the specific site identified. Identify the level of interest and influence (between 1 =low, and 10= high) each of the stakeholders has, together with their perceived attitude towards the management of the pressure, this can be identified within a workshop by individuals, or through a survey of water managers. The results should be combined to identify an average score. This allows the identification of the stakeholders with which to establish strategic relationships with as a response to the management of the pressure at the specific site. These stakeholders can therefore be considered in association with the factors within the causal analysis in Step 2.7.

Step 2.6.1 Identify and list the stakeholders associated with the high priority variables identified from the characterisation of the problem domain, and the site specific causal analysis (from Step 2.5). [*A graph of the dominance of the stakeholders identified across the factors selected, would further provide an understanding of the significant stakeholders to include with respect to the factors to be considered.*].

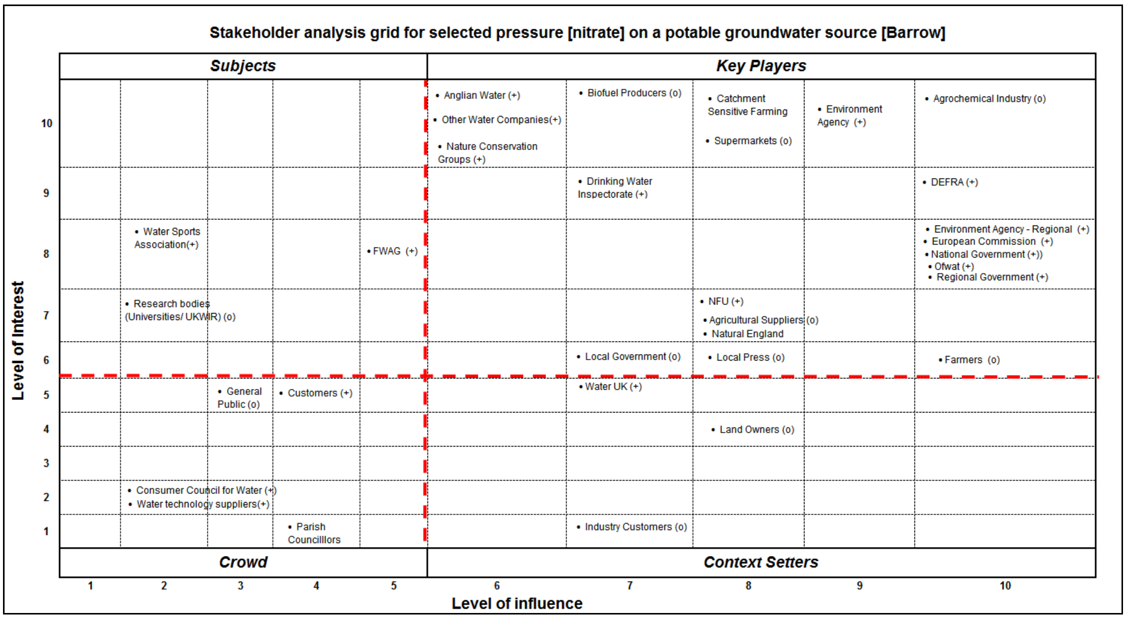
Step 2.6.2 Identify the level of interest and influence of the stakeholders with regard to the management of the specific pressure for the specific site

Step 2.6.3 Identify whether the stakeholders are supportive (+), unsupportive (-) or neutral (o) as identified in App Table 23.

App Table 23: Example stakeholder analysis table to populate the Stakeholder Grid in Step 2.6.4

Stakeholders Identified	Level of influence (1-10)	Level of interest (1-10)	Nature of support (+), (-), (o)	Stakeholder category (step 2.6.7)
Agricultural Suppliers	8	7	o	
Agrochemical Industry	10	10	o	
Anglian Water	6	10	+	
Biofuel producers	7	10	o	
Catchment Sensitive Farming Officers	8	10	+	
Consumer Council for Water	2	2	+	

Step 2.6.4 Position each stakeholder onto the Stakeholder Grid according to their level of interest and influence scores.



App Figure 11: Example Stakeholder analysis grid

Step 2.6.5 Using the 'add text' option from the draw menu, type each stakeholder and corresponding perceived level of support (-), (o) or (+) for the management of the identified pressure on the potable water source.

Step 2.6.6 Identify the significant stakeholders to be considered in the development of strategic options as those in the "context setters" and "key players" grid segments.

App Table 24: Stakeholder analysis categories (Eden and Ackerman, 1998, Reed *et al*., 2009)

Stakeholder categories	**Description**
Key players	Key stakeholders with both high interest and influence , with which close relationships would be of benefit
Context Setters	have high influence but limited interest. Therefore close relationships should be developed, to monitor and manage the potential risk they present.
Subjects	stakeholders who are supportive although lack the influential power needed to create change. Potential for collaborations of different 'subjects' may occur, which may result in greater influence.
Crowd	stakeholders with limited interest or influential power, and therefore do not need to be further engaged with.
Supportive	Stakeholders show positive support for the management of the identified pressure on the potable water source
Neutral	Stakeholders do not show a preference either way
Unsupportive	Stakeholders show negative support for the management of the identified pressure on the potable water source

Step 2.6.7 Complete the columns in App Table 23 to identify those stakeholders which require further development of strategic organisational relationships(i.e. those from Step 2.6.6). These specific stakeholders need to be incorporated into the “response” options by the water company as part of the DPSIR assessment in Step 2.7. In addition the general stakeholders identified for specific factors can be taken forward for consideration in Step 2.17, as part of the general strategic organisational response options.

Note 1: Where more than one informant provides values for perceived interest and influence, the average of the values can be taken as representative of the perceived stakeholder influence and interest with regard to the specific site and pressure of concern, which are rounded to a whole number for qualitative representation on the stakeholder grid.

Note 2: The values presented here are those derived from the Focus group workshop conducted in the initial trials of the use of stakeholder analysis and averaged for the number of perspectives given for each stakeholder. (values have been rounded to the nearest whole number for qualitative representation on the stakeholder grid).

Step 2.7: Causal analysis: DPSIR grid

Purpose: to identify the causal relationships between the factors identified which affect potable water management. Therefore the relationships are visually represented to provide an awareness of how existing responses, and water company responses can target specific driving forces, pressures, states, and impacts on the environment, water sources, water treatment or potable water supply. Hence water managers can be more informed of the holistic system and the intervention factors being used to manage the potable water supply system, which would inform where gaps may exist, whilst also identifying where resources could be removed if the D,P,S or I are being managed by other existing "responses".

Causal analysis of the factors which affect potable water management, in the context of the management of the identified pressure (e.g. nitrate) on groundwater resources within the identified site or catchment (e.g. GW/SW) are presented in a causal DSPIR grid. The representation of the high prioritised factors in the causal grid allows for the relationships between the factors to be explicitly identified, which is made transparent through a numerical referencing system. The causal analysis provides for the learning and sharing of the knowledge regarding the influential relationships between water managers when conducted as part of a workshop or focus group with active participation.

Step 2.7

Complete a Causal Analysis: Use the selected high impact/ effect factors identified for the specific site and pressure (from Step 2.4) and insert into the causal analysis grid (DPSIR grid in the Microsoft Excel 2010® workbook) including the organisational response options identified (from both Phase 1 (step 1.13) and Phase 2 (step 2.2.3, and Step 2.6).

Step 2.7.1 Bring forward the DPSIR factors identified in Step2.5 and list in the appropriate section of step 2.7.1. (Select the factors with high effect on the management of the pressure, together with those which have a high effect on the management of potable water supply.)

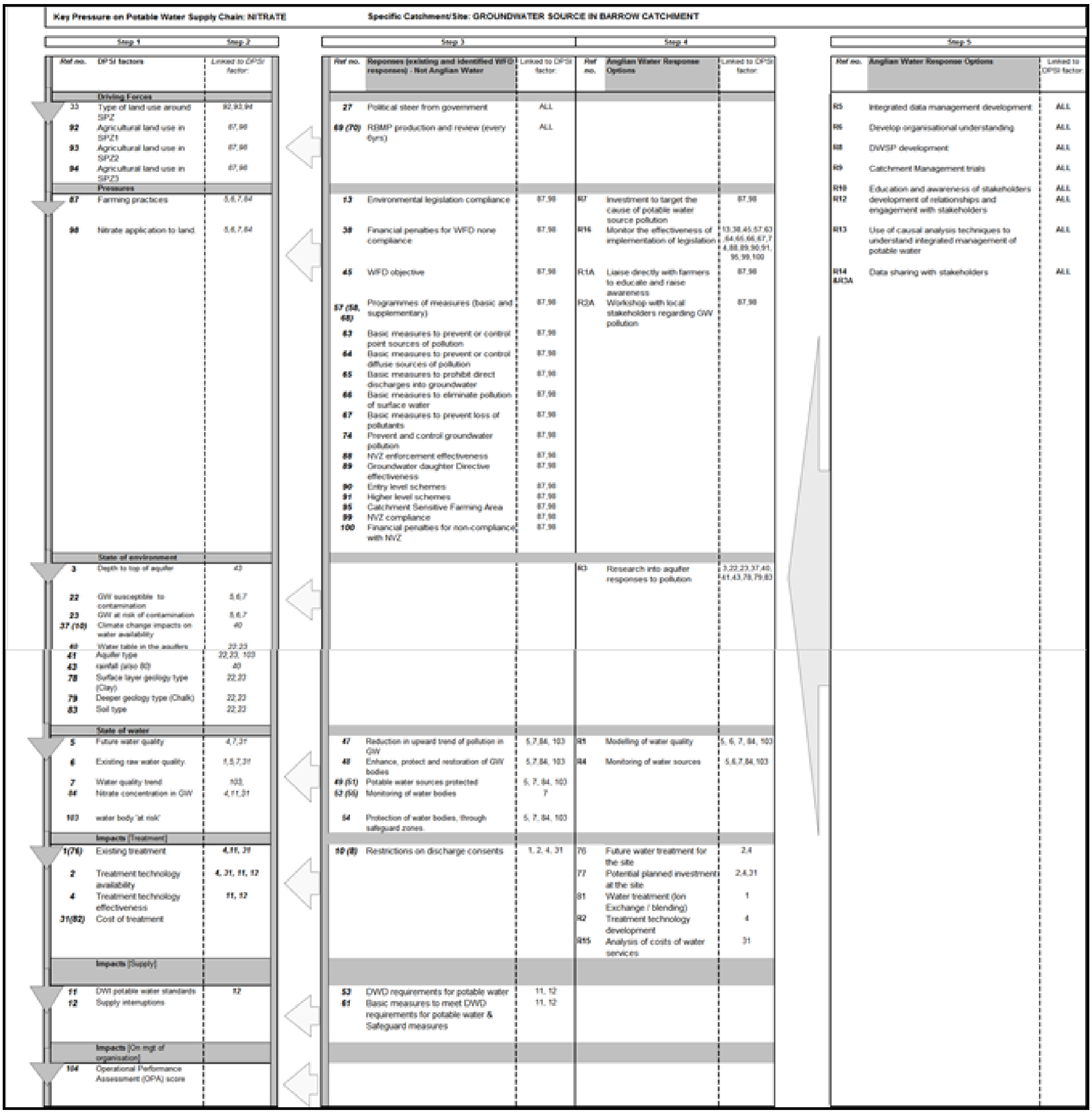
Step 2.7.2 Identify factors which are causally related, by moving down the causal chain from D to P to S to I and link to each variable through the specific reference numbers allocated, by populating the column to the right (titled step 2.7.2)

Step 2.7.3 Identify the existing or WFD responses which target the DPSI factor (link with the reference numbers) and populate the second section (step 2.7.3) in the workbook.

Step 2.7.4 Identify the additional AWS ***specific responses*** which target the DPSI factor (link with the reference numbers) (include any specific stakeholders to be engaged with from Step 2.6). and populate the second part of the second section (step 2.7.4).

Step 2.7.5 Identify the additional AWS ***general organisational*** level responses which target the DPSI factors (link with the reference numbers) (include any stakeholders to be engaged with from Step 2.6) and populate the final section of the workbook (step 2.7.5).

Step 2.7.6 The final output from this stage is a DPSIR Grid to show the qualitative relationship between the identified variables for the selected pressure and site (App Figure 12). This provides the basis of the causal relationships between factors to be taken forward for quantitative analysis within a Bayesian network.



App Figure 12: Example DPSIR causal analysis grid

Steps 2.8 – 2.15: BN development (variable identification)

Purpose: To provide a quantitative analysis of the causal relationships between the factors within the model. Ultimately to provide for an understanding into the likely impact of management interventions (either legislative or organisational) on the output variables, and hence inform potential strategic investment strategies to be considered for site and pressure specific applications.

Note: terminology changes from "factors" to "variables" for BN construction and application.

Note: Step 2.8 – 2.13 concentrate on data preparation for BN construction; Step 2.14-2.15 focus on BN construction using the BN software (e.g. Hugin or Netica).

Step 2.8

Using the DPSIR analysis as a reference identify the system boundaries and "factors" to be taken forward for analysis using Bayesian networks (e.g. combining factors, elimination of factors, or any further additional factors). Select these within the main Microsoft Excel 2010® workbook, through liaison with water managers through a workshop or focus group.

Step 2.9

Identify data sources for each selected factor (variable).

App Table 25: Data source classification

Type of data	**Description**
Electronic	Electronically available information
Hardcopy	Information available through paperback material, non-electronically.
Verbal	Information based on verbal evidence
Observational	information based on observation
Type 1 *Raw data collected by direct measurement*	Directly measured data
Type 2 *Raw data collected through stakeholder elicitation*	Data derived from stakeholder elicitation
Type 3 *Output from process-based models/ Key documents*	Data derived from electronic modelling processes, or key documents or programmes.
Type 4 *Expert opinion (theoretical calculation or best judgement)*	Data derived through informed judgement based on expert opinion.
Note: *Classification types 1 to 4 are based on Cain (2001) p. 51*	

Step 2.10

Identify data confidence (related to reliability and accuracy in App Table 26, App Table 27 and App Table 28) for each variable. Hence the data is classified according to the Ofwat criteria for the June Return 2010.

The requirement to explicitly incorporate uncertainty in the data used through liaison with the water company, has resulted in the alignment with the confidence grades used by the economic regulator Ofwat for justification of investment. The data used within the DSP and ultimate BN would be transparently represented in reporting the proposed investment options, and therefore ensuring the methodological approach is credible with the regulatory stakeholders.

The confidence grades used within the 'June Return', (an economic regulatory requirement by Ofwat), are considered to represent the level of uncertainty regarding the source of the information used to identify the investment requirements. The grades are used by companies, to provide a reasoned basis for companies to identify the reliability and accuracy of the data used to justify and represent their performance.

The grades are determined based on a qualitative reliability band from A to D and accuracy bands 1 to 6 (and additionally X) as set out below. An example of the combination is presented below.

A2 *Data based on sound records etc. (A, highly reliable) and estimated to be within +/- 5% (accuracy band 2*

App Table 26: Terminology definition for confidence grades (Ofwat, 2010b)

Reliability	Based on Ofwat guidance for June Return (2010) this band ranges from A to D. The classification of this banding can be identified in the tables provided to the right of this column.
Accuracy	Based on Ofwat guidance for June Return (2010) this band ranges from 1 to 6 including X. The classification of this banding can be identified in the tables provided to the right of this column.

App Table 27: June Return confidence grades (Ofwat, 2010b)

Reliability band	Description
A	Sound textual records, procedures, investigations or analysis properly documented and recognised as the best method of assessment.
B	As A, but with minor shortcomings. Examples include old assessment, some missing documentation, some reliance on unconfirmed reports, some use of extrapolation.
C	Extrapolation from limited sample for which Grade A or B data is available.
D	Unconfirmed verbal reports, cursory inspections or analysis.

App Table 28: June Return accuracy bands (Ofwat, 2010b)

Accuracy band	Accuracy to or within +/-	But outside +/-
1	1%	-
2	5%	1
3	10%	5%
4	25%	10%
5	50%	25%
6	100%	50%
X	Accuracy outside +/- 100 %, small numbers or otherwise incompatible.	

Incompatible combinations of reliability and accuracy bands are blocked out in the following table.

Compatible confidence grades

Accuracy band	Reliability band			
	A	**B**	**C**	**D**
1	A1			
2	A2	B2	C2	
3	A3	B3	C3	D3
4	A4	B4	C4	D4
5			C5	D5
6				D6
X	AX	BX	CX	DX

Confidence grades of A2, A3, B2 or better are expected by Ofwat. Where these are not achievable action plans to address these are required. If only A4, B3, B4, or C2 are achievable, these should be justified, and where appropriate further identification of investment to increase the confidence in the data used. These categorises should be used to inform the data used within the model constructed, and therefore provide for consistency in understanding within the end user.

With regard to the data used for the construction of BNs, Cain (2001) also identified a categorisation scheme, to record the nature of the data used to inform the development of BNs. These definitions are also considered to be appropriate to record in more detail the nature of the information used to inform the development of the BN. The table below provides an *overview of the type of information sources used by Cain (2001) where type 1 data is more preferable to type 4, although where insufficient data is available type 4 is appropriate.*

Step 2.11

Categorise the variables according to Kjaerulff and Madsen (2008) variable types, using App Table 29 and App Table 30, and as a guide.

Note: The DPSIR framework allows for the causal representation of the factors identified from the PESTEL combined with the systematic analysis of the factors affecting the potable water supply chain. To further integrate the identified factors into the development of a Bayesian network, the key factors should be considered in terms of the categorisation of variables by Kjaerulff and Madsen (2008). Through this categorisation the correct representation of the network structure can be developed, in association with the understood causal relationships.

App Table 29: Conversion of the DPSIR classified variables to the BN variables used in this research

DPSIR factors	**Description** (CIS guidance definition 2003)	**Types of BN variables** (Kjaerulff and Madsen 2008)
Driving Force	An anthropogenic activity that may have an environmental effect	Background variable
Pressure	The direct effect of the driver	Problem variable or symptom variable
State	The condition of the water body resulting from both natural and anthropogenic factors	Background variable/ problem variable/ mediating variable/ symptom variable
Impact	The environmental effect of the pressure (also considering the impact on potable water management)	Problem variable/ Mediating variable/ Symptom variable.
Response	The measures taken to improve the state of the environment (and reduce the impact of the pressures on the environment and potable water management).	Problem variable

The definitions of the BN variable types is provided in the table below, with the general structure of the causal relationships identified in the subsequent figure.

App Table 30: Bayesian network variable classification (Kjaerulff and Madsen, 2008)

BN Variable type *(Kjaerulff, 2008, p.150)*	
Background	a type of information variable: for solving a problem (represented by one or more problem variables). This is generally information already available before the problem occurred which influences the problem and symptom variables. These are normally the 'root' variables in a network.
Problem	these are the variables of interest - of which the posterior probability is the purpose of the construction of the Bayesian network . The values of the problem variables cannot be observed. These are also known as `*hypothesis variables*` and can be related to ; diagnoses, classifications, predictions, decisions which are to be made.
Mediating	the variables are unobservable, and are primarily used to ensure correct conditional dependence or independence properties in the network. The parents of mediating variables are normally problem or background variables, with symptom variables as children.
Symptom	symptom information can be observed, as a consequence of the presence of a problem, therefore is available after the occurrence of a problem. (problem variables have causal influences on symptoms variables). Both problem and background variables are parents of symptom variables.
BN variable category *(Kjaerulff, 2008)*	
Chance	Represent random events and defined as " an exhaustive set of mutually exclusive events" which is also referred to as the domain of the variable. (events can be; states/ levels/ values/ choices/options etc)
Decision	Represent choices made, or interventions regarding the variables in the domain.
Utility	Represent the value of a problem domain for a particular variable of concern, e.g. decision criteria.
BN variable kind* *(Kjaerulff, 2008)*	
Discrete	variable which represents individual values
Continuous	variable which represents a continuous range of values
BN Variable sub-type *(Kjaerulff, 2008)*	
Labelled	separate text labels for each state
Boolean	yes or no states
Numbered	individual numbered states
Interval	intervals or ranges to represent quantities of the states of the variables.
*NB: *the functionality of the Bayesian networks is simpler with discrete nodes, which reduce the amount of complex computations required. Although this would be an area for further development, to establish if continuous variables can be used to inform further investment decisions.*	

Step 2.12

Identify an abbreviated name to reference the variable within the network (using an underscore (_) instead of a space e.g. groundwater quality = GW_Quality)

Step 2.13

Identify the potential states of variables (using analysis of data when available or expert opinion)

At this point within the Microsoft Excel® workbook a transparent record of data used to populate the BN within Steps 2.14 -2.15 is generated (for example App Table 31*).*

App Table 31: Example of a table to identify and classify the types of variables

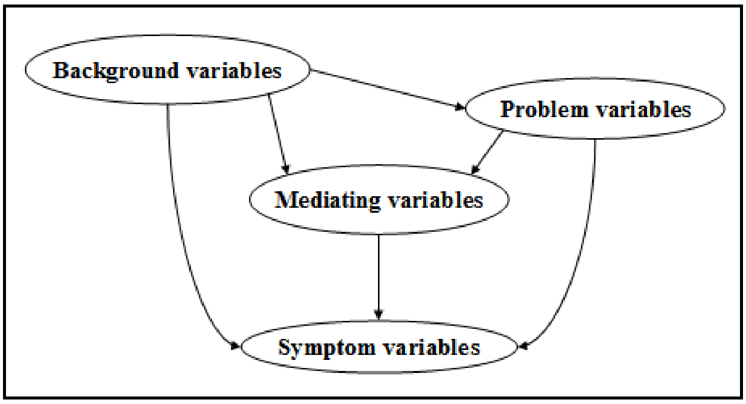
Variable name	**Abb. name**	**Description**	**Type of variables**	**Sub-type of variable**	**Distribution**	**States**	**Data source**
As per PESTEL and DPSIR.	For use in BN	Further info	Background, Problem, Information, mediating and symptom variables. [Decision/ State/ Utility]	Boolean, interval, labelled, numbered, utility	Continuous, discrete	[range of states - Specific to variables]	External/ internal data for each variable.

Note: To ensure transparency of the use of these methods and the subsequent development of the Bayesian network, a transparent record of the nature of the variables identified, and their classification should be made. This is to allow for an auditable record of the assumptions made through the construction of subsequent Bayesian networks. The table below provides an example of a table to use. Once the variables have been classified into the various types, as per the categorisation by Kjaerulff and Madsen (2008) the structure of the network can be constructed following the relationships previously identified.

The use of Bayesian network software (e.g. Hugin A/S expert) is required to construct the network. The verification of the network with domain experts is required to ensure the developed Bayesian network represents the problem domain.

Once the network is constructed the states of the variables are required to be identified, either from data to inform the nature of the states, or based on expert opinion. The states need to be 'mutually exclusive and collectively exhaustive'. Therefore the states cannot be counted twice, and in total should sum to one, hence have one distribution function. These need to be entered into the Bayesian network for each variable as part of the structure.

Step 2.14 Use variable data for the construction of the Bayesian Network within the Bayesian Network Software (e.g. Hugin Expert A/S). This can be conducted manually using the structural template proffered by Kjaerulff and Madsen (2008) (App Figure 13), or through structured learning using automatic algorithms within the BN software, although need to have data sets available for each of the variables.)



App Figure 13: General causal structure for a probabilistic network (Kjaerulff and Madsen 2008 p.153).

Step 2.15 Identify conditional probabilities (via data sources e.g. expert opinion [using App Figure 14] or deterministic modelled data when available) for variables, and verify model through a workshop of water managers or experts (hence peer review due to limited data for predictions of the future for some variables e.g. impact of legislation implementation).

Certain	Very Likely	Likely	Probable	Fifty-fifty	Not probable	Unlikely	Very unlikely	Impossible
1	0.99	0.9	0.8	0.5	0.2	0.1	0.01	0

App Figure 14: Mapping of statements of probability to probabilities (modified from Kjaerulff and Madsen, 2008 p.165)

Step 2.16: Scenario Analysis

Purpose: To provide an understanding of the range of likely outcomes from the various management options and their success in managing the potable water resource.

Step 2.16

Identify scenarios with water manager for the network based on variables considered to be more certain. Conduct scenario analysis through the Bayesian network to identify the implications of a change in the problem variables, or the type or level of organisational management interventions to manage the selected pressure.

Step 2.16.1 Identify key assumptions (including water company investment options) to be considered in the development of alternative scenarios (e.g. baseline scenario, worst case and best case scenario) related to the variables contained within the BN. (App Table 32).

App Table 32: Example assumptions for scenario analysis

Scenario	Description and assumptions
Baseline	Baseline conditions with background data for current situation, combined with assumptions made for the future states of the variables.
Worst case	Baseline conditions, with all legislative measures designated, although with assumed non-compliance across all the legislative measures to control nitrate pollution over all RBMP (both NVZ and WFD measures). All alternative sources of water are contaminated to above 45 mg/l. No AW catchment management considered.
Best Case	Compliance with all legislative measures to control nitrate, assumed through effective enforcement through the Environment Agency and stakeholder attitudinal change to support the WFD objectives. AW catchment management is implemented across all RBMPs, as Ofwat accepts it as a viable investment option. Alternative blend water becomes < 45 mg/l after AMP 7 (based on the assumption of improved management of nitrate at Thornton and Goxhill through improved farm management practices as a result of catchment sensitive farming initiative.)

Step 2.16.2 Identify the key output/ problem variables and states to be considered and track the changes in the probability values. (e.g. Raw Water quality to feed into the Asset Plus system to manually modify the risk profile for the asset performance for water treatment) (App Table 33).

App Table 33: Example of scenario analysis output

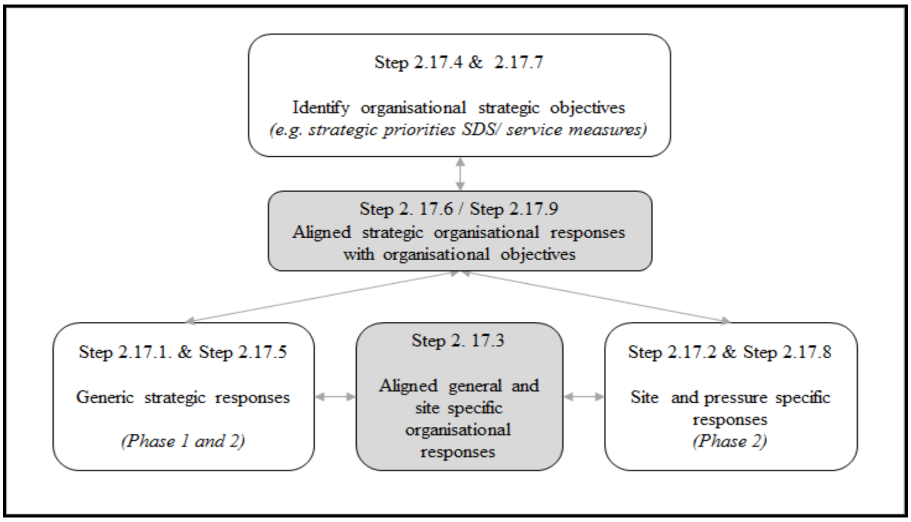
	Probability of state of variable					
Output variable	***Scenario 1 - Baseline***		***Scenario 2 – Worst Case***		***Scenario 3 – Best Case***	
State of variable	***< 45 mg/l***	***> 45mg/l***	***< 45 mg/l***	***> 45mg/l***	***< 45 mg/l***	***> 45mg/l***
Raw water quality 2010	0	100	0	100	0	100
Raw water quality 2015	5.74	94.26	1.94	98.06	1.37	98.63
Raw water quality 2020	16.31	83.69	3.46	96.54	6.11	93.89
Raw water quality 2025	25.9	74.1	7.16	92.84	23.52	76.48
Raw water quality 2030	29.59	70.41	10.6	89.4	39.27	60.73

Enter the BN model outputs from the initial baseline scenario without investment into Asset Plus as an “Asset Plus **Pre-Investment service measure assessment**”. Then enter outputs from the BN model when an intervention is selected within the identified scenario, as an “Asset Plus **Post-Investment service measure assessment**”. The associated cost of the specified investment should also be identified including an operational expenditure (OPEX) and any repeat capital expenditure (CAPEX) costs, and input into Asset Plus. A Cost Benefit Net Present Value (NPV) assessment can then be calculated within Asset Plus.

Step 2.16.3 Identify any proposed strategic investment required for each scenario for the different time periods to respond to the changes in the key problem variables (e.g. raw water quality) *[In addition an optional Value of Information analysis from within BN, can be performed to assess the value of identifying new information for the system on investment decision making.]*

Step 2.17: Strategic options analysis

Purpose: Qualitative assessment of the relationship between the required investment responses identified through the general environmental analysis and the site specific investment requirements to further inform the nature of the strategic organisational response options.



App Figure 15: Overview of the strategic option analysis of identified organisational responses from the steps within Phase 1 and Phase 2, and the organisational objectives.

Step 2.17

Identify strategic options through evaluation of organisational responses identified in Step 1.13 and investment options for the identified site specific scenario's from Step 2.16 against the organisational strategic priorities as identified in the strategic direction statement.

Cross-reference and integration matrix of site specific and general organisational response options (Step 2.17.1 – 2.17.3)

Purpose: Integrated cross-reference matrix for the strategic site specific requirements and the organisational responses to ensure strategic alignment of investment options

Step 2.17.1 Identify the strategic organisational responses identified from the organisational analysis (step 1.13) and enter into the matrix column headings.

Step 2.17.2 Identify the strategic stakeholders (step 2.6), site specific response options (step 2.7.4 and Step 2.7.5), (and key variables from the optional VoI analysis step 2.16) to be considered within the development of the general organisational response options and enter into the left hand column.

Step 2.17.3 Identify the integration of the Phase 2 organisational responses, with the Phase 1 generic organisational responses. [Therefore the site specific options are integrated within the wider strategic organisational response options to form a consistent development of options to be considered in the development of organisational strategy in the management of the potable water supply chain.]

Alignment of general organisational responses to strategic organisational objectives (Step 2.17.4 – 2.17.6)

Purpose: Qualitative assessment of the alignment of the proposed organisational responses to the strategic organisational priorities and service delivery measures

Step 2.17.4 Identify the organisational strategic priorities and service measures to be considered in the evaluation of strategic response options from the Strategic Direction Statement (2007) and the AMP Service measures for non-infrastructure (above ground assets).

Step 2.17.5 Identify the strategic organisational responses (interventions) from Phase 1 (and previous strategic option analysis table).

Step 2.17.6 Assess the interventions against the organisational priorities and service measures (identify which ones they would support)

Alignment of site specific organisational responses to strategic organisational objectives (Step 2.17.7 – 2.17.9)

Purpose: Qualitative assessment of the site specific investment requirements identified and their alignment with the strategic priorities and service measures.

Step 2.17.7 Identify the organisational strategic priorities and service measures to be considered in the evaluation of strategic response options from the Strategic Direction Statement (2007) and the AMP Service measures for non-infrastructure (above ground assets) insert across column heading in the matrix.

Step 2.17.8 Identify the site specific responses (interventions) from Phase 1 (and previous strategic option analysis table) and insert in the left hand column.

Step 2.17.9 Assess the site specific intervention options against the organisational priorities and service measures (identify which ones they would support)

Further quantitative analysis of site specific strategic options using Asset Plus+

Step 2.17.10 Site specific investment requirements regarding the investment in treatment assets require the revised probability value to be inserted into the Asset Plus investment management system, to update the risk profile for the performance of the asset (e.g. ion exchange) over time. Therefore the timing of further investment can be identified (either brought forward, maintained or deferred)

App Table 34: Example Integrated cross-reference matrix for the strategic site specific requirements and the organisational responses to ensure strategic alignment of investment options

	Output from Phase 1 and Phase 2 analysis to be considered in the development of the strategic organisational response (intervention) options for the Barrow catchment	Organisational responses identified in Phase 1							
		R1	R2	R3	R4	R5	R6	R7	R8
Stakeholder analysis	Engagement with **key players** and **context setters** as identified in the Stakeholder analysis	✓	✓	✓	✓	✓	✓	✓	✓
Causal analysis *(additional site specific responses)*	Liaise directly with farmers in SPZ to educate and raise awareness of nitrate pollution (R1A)	✓		✓	✓	✓	✓	✓	✓
	Workshop with local stakeholders regarding GW pollution (R2A)				✓	✓	✓	✓	
	Data sharing with stakeholders (R3A)	✓		✓	✓	✓	✓		
	Ion Exchange treatment requirements	✓	✓			✓			
VoI key variables requiring further information	Risk of GW pollution 2015-2021	✓		✓	✓	✓	✓		✓
	uncontrolled diffuse sources in SPZ RBMP 2								✓
	uncontrolled point sources in SPZ RBMP 2								✓

App Table 35: Example qualitative assessment of the alignment of the proposed organisational responses to the strategic organisational priorities and service delivery measures

		Organisational strategic priorities (SDS, 2007)				***Service delivery measure****
Ref	**Strategic organisational options****	**Increase the resilience and reliability of our water and wastewater services**	**Secure and conserve water resources**	**Anticipate and invest for growth in our region**	**Improve our efficiency and flexibility**	**Physiochemi cal water quality failure** (e.g. nitrate)
	Organisational level					
R1	Modelling of future water quality and quantity changes on requirements for water treatment	✓	✓	✓	✓	✓
R2	Further development of innovative treatment technologies	✓	✓		✓	✓
R3	Research and investigation in aquifer characteristics and responses to pollution	✓	✓		✓	✓

Note * *service delivery measure for reasons for failure of water non-infrastructure (above ground) assets (AMP Part B, 2009*
***AW Interventions to support organisational strategy, and address water infrastructure and non-infrastructure service measures*

App Table 36: Example of Qualitative Assessment of Site specific strategic options against organisational and industry criteria (AWS, SDS, 2007)

		Organisational strategic priorities (SDS, 2007)						
Ref	**Strategic site specific options** *(AW Interventions to support organisational strategy, and address water infrastructure and non-infrastructure service measures)*	**Increase the resilience and reliability of our water and wastewater services**	**Secure and conserve water resources**	**Anticipate and invest for growth in our region**	**Improve the environment in our region**	**Mitigate and adapt to climate change impacts**	**Improve our efficiency and flexibility**	**Keep bills at current affordability**
Scenario	**Site Specific level**							
Best Case	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, although it is reducing to a 60% probability, by 2030. Investment in catchment management activities (R1A, R2A, R3A) to influence the reduction of nitrate pollution at the catchment level, through stakeholder engagement, data sharing, education and awareness raising with local stakeholders.	✓	✓		✓			
Baseline	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, although it is reducing to a 70% probability, by 2030. Initial investment in Catchment Management for RBMP 1.	✓			✓			
Worst case	Ion exchange treatment should be maintained due to raw water quality being > 45 mg/l, with a probability of 89% by 2030.	✓						

App Table 37: Example list of "key players" and hence priority stakeholders to engage with for potable water management as identified from the stakeholder analysis (Step 2.6)

Stakeholders Identified	Supportive (+)	Neutral (o)	Unsupportive (-)	Stakeholder classification
Agricultural Suppliers		o		**Key Player**
Agrochemical Industry		o		**Key Player**
Anglian Water	+			**Key Player**
Biofuel producers		o		**Key Player**
Catchment Sensitive Farming Officers	+			**Key Player**

OUTPUT from Hybrid-DSP:

The main outputs from the Hybrid-DSP focus on a qualitative assessment and identification of investment options for both the general organisational strategic response to the changes affecting potable water management, and a semi-quantitative output from the BN analysis for site specific investment options (Forward propagation) of investment decisions, or Forward propagation of site specific conditions on the variable of interest (e.g. groundwater quality) and the potential changes over time.

1. Investment options for organisation at a general level (Phase 1)
2. Investment options for a specific site (Phase 2)

Both of these outputs are combined and assessed against the organisational Strategic Direction Statement to check alignment with investment priorities.

End of Phase 2

Appendix: Optional stage of VoI for Step 2.15 – Step 2.16 in BN software

BN software : Value of Information Analysis to be conducted during Step 2.15- 2.16

Step	Value of Information analysis
Step 1	Select key variables within the Bayesian network which are required to be further informed to reduce the uncertainty of the state of the variable.
Step 2	Conduct VoI analysis using the software to identify key variables for which evidence would reduce the uncertainty of the Hypothesis variable. Identify the variables, the uncertainty associated with the variable and the related value of information ratio for observed variables.
Step 3	Identify the variables for which gathering of information and evidence would have the most impact on reducing the uncertainty of the hypothesis variable of concern.
Step 4	Consider these variables in the assessment of strategic options in Step 2.17.

Appendix F

Hybrid-DSP demonstration results

In chapter 6 the Hybrid-DSP was demonstrated with results from each step of the process. The summary results are presented in the main chapter, although the detailed results are presented in this Appendix.

The table below highlights all the factors taken forward from the prioritisation assessment conducted as part of Step 2.5.

App Table 38: All high priority factors to be taken forward for analysis using the DPSIR grid in Step 2.7

Ref No.	WFD Ref	Factor name	Description
1	-	Existing treatment	Existing water treatment for a site
2	-	Treatment technology availability	the type of technology available for the treatment of potable water to the required DWD standards.
3	-	Depth to top of aquifer	depth to the top of the aquifer used for potable water supply
4	-	Treatment technology effectiveness	The effectiveness of the treatment technology used to ensure potable water supplies.
5	-	Future water quality	the quality of the water into the future (which may be subject to the effect of legislative changes).
6	-	Existing raw water quality	Water quality of potable sources used for supply.
7	-	Water quality trend	The trend of water quality over time, related to the concentration of the pollutant.
8	-	Discharge consents for wastewater	Wastewater discharge consent restrictions for discharge into water bodies.
10	-	Restrictions on discharge consents	Potential restriction on discharge consents
11	-	DWI potable water standards	DWI potable water standards for potable water supply.
12a	-	Future treatment provision	potential requirement for future treatment
13	-	Environmental legislation compliance	Environmental legislation compliance requirements (e.g. UWWTD, Habitats Directive)
16	-	Climate change	changes in weather patterns are unpredictable with droughts and floods a potential risk.
22	-	GW susceptible to contamination	Susceptibility of groundwater to contamination from pollutants
23	-	GW at risk of contamination	At risk of contamination is linked to the susceptibility of the GW and the presence of point

Ref No.	WFD Ref	Factor name	Description
			or diffuse sources of pollutant.
25	-	Drinking Water Safety Plan development	DWI requirement for a DWSP to be developed to reduce risks to potable water supply
26	-	Ofwat position with regard to Catchment Management intervention	Ofwat perspective on the viability of catchment management as an investment option.
31	-	Cost of treatment	Cost of the provision of treatment
40	-	Water table in the aquifers	the level of the water table would influence the availability of water sources
41	-	Aquifer type	the type of aquifer may determine the nature of the water source and potential contamination of the source.
47	4 (1) (b) (iii)	Reduction in upward trend of pollution in GW	Aim of the WFD is to reduce the upward trend associated with the pollution entering into the groundwater.
48	4(1)(b)(ii)	Enhance, protect and restoration of GW bodies	measures to protect, restore and enhance GW bodies to achieve GW good status are to be developed.
49	4(1) (c)	Potable water sources protected	Sources of water used for drinking water are classed as protected areas.
51	6	Protected areas	Establishment of a register of protected areas
53	7 (2)	DWD requirements for potable water	under the water treatment regime applied the resulting water (for potable supply) must meet the requirements of Directive 98/83/EC.
54	7 (3)	Protection of water bodies, through safeguard zones.	Water bodies identified for human consumption are protected to avoid deterioration in quality to reduce the level of purification treatment required. Designation as Drinking Water Protection Areas (DrWPAs), and establishment of safeguard zones
55	8	Monitoring plans	establish monitoring programmes for water status for SW, GW and protected areas
57	11 (2)	Programmes of measures	PoM should include both basic and supplementary measures.
58	11 (3) (a)	Basic measures	those measures required to implement Community legislation for the protection of water, including measures required under the legislation specified in Article 10 (combined approach for point and diffuse sources) and in part A of Annex VI (list of measures to be included);
61	11 (3) (d)	Basic measures to meet DWD requirements for potable water & Safeguard measures	measures to meet the requirements of Article 7 (waters used for the abstraction of drinking water), including measures to safeguard water quality in order to reduce the level of purification treatment required for the production of drinking water;
63	11(3)(g)	Basic measures to prevent or control point sources of pollution	for point source discharges liable to cause pollution, a requirement for prior regulation, such as a prohibition on the entry of pollutants into water, or for prior authorisation, or registration based on general binding rules, laying down

Ref No.	WFD Ref	Factor name	Description
			emission controls for the pollutants concerned,
64	11(3)(h)	Basic measures to prevent or control diffuse sources of pollution	for diffuse sources liable to cause pollution, measures to prevent or control the input of pollutants.
67	11 (3)(l)	Basic measures to prevent loss of pollutants	any measures required to prevent significant losses of pollutants from technical installations, and to prevent and/or to reduce the impact of accidental pollution incidents
68	11	Supplementary measures	'Supplementary' measures are those measures designed and implemented in addition to the basic measures, with the aim of achieving the objectives established pursuant to Article 4. Part B of Annex VI contains a non-exclusive list of such measures.
74	17	Prevent and control groundwater pollution	measures to prevent and control groundwater pollution to achieve 'good chemical status' in accordance with Art. 4 (1) (b) and shall be adopted within 2 yrs of coming into force of the WFD (hence 2002).
76		Future water treatment for the site	future treatment options available for the site
78		Surface layer geology type (Clay)	geology in first 10 metres of B/H
79		Deeper geology type (Chalk)	Geology after 10 metres into B/H
80		Rainfall	Average annual rainfall for the area
81		Water treatment (Ion Exchange/ blending)	type of water treatment to remove the specific pressure identified.
82		Cost of treatment	cost of water treatment required to remove pollutant from raw water
84		Nitrate concentration in GW	Concentration of nitrate in groundwater within potable water source.
88		NVZ enforcement effectiveness	the level and effectiveness of enforcement of the NVZ
89		Groundwater Daughter Directive effectiveness	the level and effectiveness of the requirements of the Groundwater Daughter Directive 2006/118/EC
92		Agricultural land use in SPZ1	identification of the use of the agricultural land within source protection zone 1 (minimum of 50 m) from Borehole
93		Agricultural land use in SPZ2	Identification of the use of the agricultural land within source protection zone 2 (250 - 500m) from Borehole
94		Agricultural land use in SPZ3	Identification of the use of the agricultural land within source protection zone 3 the source catchment protection zone around the Borehole

Ref No.	WFD Ref	Factor name	Description
95		Catchment Sensitive Farming Area	Location is subject to provisions made under the catchment sensitive farming initiative to reduce pollution of water bodies.
98		Nitrate application to land	amount of nitrate applied to the land (includes both livestock and fertiliser)
99		NVZ compliance	Compliance with the NVZ requirements for nitrate management
101		Drinking Water Protected Area	Abstraction source designated as a DrWPA
102		Safeguard Zone designation	Abstraction source designated as a safeguard zone
103		Water body 'at risk'	At Risk' status of water body where a rising trend is present resulting in water body not meeting WFD objectives
R3		Research into aquifer responses to pollution	Research and investigation in aquifer characteristics and responses to pollution
R5		Integrated data management development	development of integrated data management (internal and external data) at a catchment level (link into RBMP, legislation requirements, land use, water quality, climate, treatment requirements)
R6		Develop organisational understanding	Organisational understanding of current and future risks to water supplies.
R10		Education and awareness of stakeholders	education and awareness raising of general public, and customers regarding efficient and sustainable water use (incl schools).
R12		Development of relationships and engagement with stakeholders	Engagement with stakeholders regarding management of pollution in catchments
R13		Use of causal analysis techniques to understand integrated management of potable water	Development of causal analysis techniques to increase understanding of relationships between identified factors affecting the management of the potable water supply chain.
R16		Monitor the effectiveness of implementation of legislation	Monitor the effectiveness of legislation implementation/ measures (e.g. safeguard zones, water protection zones, DrWPAs)
R1A		Liaise directly with farmers to educate and raise awareness	Liaise with farmers to educate and raise awareness of nitrate pollutants in potable water sources
R2A		Workshop with local stakeholders regarding GW pollution	Increase engagement and awareness across a broad range of stakeholders regarding GW pollution
R3A		Data sharing with stakeholders	Share data with stakeholders to increase awareness and understanding of impacts within the catchment

App Table 39: Data sources and confidence used in the BN construction (Step 2.8-2.10)

Note: Type 1= Raw data collected by direct measurement, Type 2= Raw data collected through stakeholder elicitation; Type 3= Output from process-based models/ Key documents; Type 4 = Expert opinion (theoretical calculation or best judgement)

BN ref number	***Type of variable***	***Original Ref.***	***Name of factor***	Electronic	Hardcopy	Verbal	Observational	**Type 1**	**Type 2**	**Type 3**	**Type 4**	Other	*Specify data source*	*Reliability*	*Accuracy*
BN 01	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*99*	*NVZ compliance*	×	×	×	✓	×	×	✓	✓	✓	Nitrate Pollution Prevention Regulations combined with inferred application from observations.	A	3
BN 02	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*88*	*NVZ enforcement effectiveness*	×	×	×	✓	×	×	×	✓	✓	informed judgement, based on limited data from EA regarding NVZ failures across the region.	C	4
BN 03	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*88*	*NVZ enforcement effectiveness*	×	×	×	✓	×	×	×	✓	✓	informed judgement, based on limited data from EA regarding NVZ failures across the region.	C	4
BN 04	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*98*	*Nitrate application to land*	×	×	×	✓	×	×	✓	✓	✓	Indicated/ inferred from crop type/ visual inspection of storage of nitrate (e.g. manure heaps) and Nitrate Directive, and nitrate Regulations guidelines for nitrate application	C	5
BN 05	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*98*	*Nitrate application to land*	×	✓	×	✓	×	×	✓	✓	✓	Indicated/ inferred from crop type/ visual inspection of storage of nitrate (e.g. manure heaps) and Nitrate Directive, and nitrate Regulations guidelines for nitrate application	C	5
BN 06	*General factor*	*23*	*GW at risk of contamination*	✓	✓	✓	✓	✓	✓	✓	✓	×	Informed judgement, for the requirement for a mediating variable in the Bayesian Network	C	5
BN 07	*Phase 2 Step 2.2.2 Organisational response*	***R9***	*Catchment Management trials*	×	×	×	×	×	×	×	✓	×	No specific information as responses are to be evaluated once in place.	D	X

Note: Type 1= Raw data collected by direct measurement, Type 2= Raw data collected through stakeholder elicitation; Type 3= Output from process-based models/ Key documents; Type 4 = Expert opinion (theoretical calculation or best judgement)															
BN ref number	***Type of variable***	***Original Ref.***	***Name of factor***	Electronic	Hardcopy	Verbal	Observational	**Type 1**	**Type 2**	**Type 3**	**Type 4**	Other	*Specify data source*	*Reliability*	*Accuracy*
BN 08	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*99*	*NVZ compliance*	×	×	×	✓	×	×	✓	✓	✓	Nitrate Pollution Prevention Regulations combined with inferred application from observations.	A	3
BN 09	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*99*	*NVZ compliance*	×	×	×	✓	×	×	✓	✓	✓	Nitrate Pollution Prevention Regulations combined with inferred application from observations.	A	3
BN 10	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*88*	*NVZ enforcement effectiveness*	×	×	×	✓	×	×	×	✓	✓	informed judgement, based on limited data from EA regarding NVZ failures across the region.	C	4
BN 11	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*88*	*NVZ enforcement effectiveness*	×	×	×	✓	×	×	×	✓	✓	informed judgement, based on limited data from EA regarding NVZ failures across the region.	C	4
BN 12	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*98*	*Nitrate application to land*	×	✓	×	✓	×	×	✓	✓	✓	Indicated/ inferred from crop type/ visual inspection of storage of nitrate (e.g. manure heaps) and Nitrate Directive, and nitrate Regulations guidelines for nitrate application	C	5
BN 13	*General factor*	*23*	*GW at risk of contamination*	✓	✓	✓	✓	✓	✓	✓	✓	×	Informed judgement, for the requirement for a mediating variable in the Bayesian Network	C	5
BN 14	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*98*	*Nitrate application to land*	×	✓	×	✓	×	×	✓	✓	✓	Indicated/ inferred from crop type/ visual inspection of storage of nitrate (e.g. manure heaps) and Nitrate Directive, and nitrate Regulations guidelines for nitrate application	C	5
BN 15	*Phase 2 Step 2.2.2 Organisational response*	***R16***	*monitor the effectiveness of implementation of legislation*	×	×	×	×	×	×	×	✓	×	No specific information as responses are to be evaluated once in place.	D	X

Note: Type 1= Raw data collected by direct measurement, Type 2= Raw data collected through stakeholder elicitation; Type 3= Output from process-based models/ Key documents; Type 4 = Expert opinion (theoretical calculation or best judgement)

BN ref number	***Type of variable***	***Original Ref.***	***Name of factor***	Electronic	Hardcopy	Verbal	Observational	**Type 1**	**Type 2**	**Type 3**	**Type 4**	Other	*Specify data source*	*Reliability*	*Accuracy*
BN 16	*WFD factor*	*48*	*enhance, protect and restoration of GW bodies*	✓	✓	✓	✓	×	×	✓	✓	×	RBMP contain the measures which aim to achieve this objective.	A	3
BN 16	*WFD factor*	*49*	*Potable water sources protected*	✓	✓	✓	×	×	×	✓	✓	×	RBMP identifies the water sources which are protected.	A	2
BN 16	*WFD factor*	*51*	*Protected areas*	✓	✓	×	×	×	×	✓	✓	×	RBMP	A	3
BN 17	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*102*	*Safeguard Zone designation*	✓	✓	×	×	×	×	✓	×	×	RBMP	A	1
BN 18	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*101*	*Drinking Water Protected Area*	✓	✓	×	×	×	×	✓	×	×	RBMP	A	1
BN 19	*General factor*	*23*	*GW at risk of contamination*	✓	✓	✓	✓	✓	✓	✓	✓	×	Informed judgement, for the requirement for a mediating variable in the Bayesian Network	C	5
BN 19	*Phase 2 Step 2.2.1 Pressure specific characteristics*	*103*	*water body 'at risk'*	✓	✓	×	×	×	×	✓	×	×	RBMP	A	1
BN 20	*General factor*	*42*	*Soil type*	✓	×	×	×	✓	×	✓	×	×	CatchIS information	A	2
BN 20	*Site specific factor*	*83*	*Soil type*	✓	✓	×	×	×	×	✓	×	✓	Use of CatchIS database for soil type around specific borehole locations.	A	3

Note: Type 1= Raw data collected by direct measurement, Type 2= Raw data collected through stakeholder elicitation; Type 3= Output from process-based models/ Key documents; Type 4 = Expert opinion (theoretical calculation or best judgement)

BN ref number	***Type of variable***	***Original Ref.***	***Name of factor***	Electronic	Hardcopy	Verbal	Observational	**Type 1**	**Type 2**	**Type 3**	**Type 4**	Other	*Specify data source*	*Reliability*	*Accuracy*
BN 21	*General factor*	*22*	*GW susceptible to contamination*	✓	✓	✓	✓	✓	✓	✓	✓	✗	Susceptibility of Groundwater to pollutants from point and diffuse discharge sources indicate the risk of the water body to contamination. Theoretical principles identified from the EA GP3 - Part 2 technical report for protection of groundwater's. AW internal CRAG data, DWSP data.	C	5
BN 22	*General factor*	*3*	*Depth to top of aquifer*	✓	✓	✓	✓	✓	✗	✓	✓	✗	operational manuals, GW asset database (internal) based on CRAGS information.	A	1
BN 23	*General factor*	*22*	*GW susceptible to contamination*	✓	✓	✓	✓	✓	✓	✓	✓	✗	Susceptibility of Groundwater to pollutants from point and diffuse discharge sources indicate the risk of the water body to contamination. Theoretical principles identified from the EA GP3 - Part 2 technical report for protection of groundwater's. AW internal CRAG data, DWSP data.	C	5
BN 24	*WFD factor*	*47*	*Reduction in upward trend of pollution in GW*	✓	✗	✗	✗	✓	✗	✓	✓	✗	internal monitoring data identifies the historical trend of the pollutant concentration in the groundwater.	A	3
BN 25	*General factor*	*6*	*Existing raw water quality*	✓	✗	✓	✓	✓	✗	✗	✓	✗	Crystal QD warehouse database of monitoring data.	A	2
BN 26	*General factor*	*1*	*Existing treatment*	✓	✓	✓	✓	✓	✗	✓	✗	✗	Site visits, and operational manuals provide information related to the existing treatment for a site.	A	1
BN 27	*General factor*	-	*alternative source*	✗	✓	✓	✓	✓	✓	✓	✓	✗	site visit, operational manual for the site, liaison with site manager, water quality data.	A	1

Note: Type 1= Raw data collected by direct measurement, Type 2= Raw data collected through stakeholder elicitation; Type 3= Output from process-based models/ Key documents; Type 4 = Expert opinion (theoretical calculation or best judgement)

BN ref number	***Type of variable***	***Original Ref.***	***Name of factor***	Electronic	Hardcopy	Verbal	Observational	**Type 1**	**Type 2**	**Type 3**	**Type 4**	Other	*Specify data source*	*Reliability*	*Accuracy*
BN 28	*General factor*	*6*	*Existing raw water quality*	✓	×	✓	✓	✓	×	×	✓	×	Crystal QD warehouse database of monitoring data.	A	2
BN 28	*General factor*	*11*	*DWI potable water standards*	✓	✓	✓	×	✓	✓	✓	✓	×	Standards available through regulations.	A	1
BN 29	*General factor*	*11*	*DWI potable water standards*	✓	✓	✓	×	✓	✓	✓	✓	×	Standards available through regulations.	A	1
BN 30	*Site specific factor*	*81*	*Water treatment (Ion Exchange/ blending)*	✓	✓	✓	✓	✓	×	✓	×	×	Operational Manuals, site visits.	A	1
BN 31	*General factor*	*11*	*DWI potable water standards*	✓	✓	✓	×	✓	✓	✓	✓	×	Standards available through regulations.	A	1
BN 32	*General factor*	*11*	*DWI potable water standards*	✓	✓	✓	×	✓	✓	✓	✓	×	Standards available through regulations.	A	1
BN 33	*General factor*	*7*	*Water quality trend*	✓	×	×	×	✓	×	✓	✓	×	Trend data available from Crystal QD warehouse for individual boreholes.	A	2
BN 34	*General factor*	*6*	*Existing raw water quality*	✓	×	✓	✓	✓	×	×	✓	×	Crystal QD warehouse database of monitoring data.	A	2
BN 34	*General factor*	*23*	*GW at risk of contamination*	✓	✓	✓	✓	✓	✓	✓	✓	×	Informed judgement, for the requirement for a mediating variable in the Bayesian Network	C	5

App Table 40: Definition of BN variable types, name and states (Step 2.11-2.13)

BN ref number	**BN variable type**	**BN variable category**	**BN variable kind**	**BN variable subtype**	**Abbreviated name for variable in Bayesian network**	**Name the state/s to be used in the model**	**Definition of states**	**location in the network**
BN 01	Mediating	Chance	Discrete	Labelled	**stakeholder NVZ compliance**	compliant or non-compliant	Stakeholders complying with NVZ or not, through observation of activities or self-assessment.	catchment management variables prior to the WFD implementation
BN 02	Mediating	Chance	Discrete	Labelled	**existing NVZ designation**	designated, not designated	dependent on stakeholder compliance and designation status of NVZ	catchment management variables prior to the WFD implementation
BN 03	Mediating	Chance	Discrete	Labelled	**effectiveness of NVZ**	effective, not effective, no measures	dependent on stakeholder compliance and designation status of NVZ	catchment management variables prior to the WFD implementation
BN 04	Mediating	Chance	Discrete	Labelled	**uncontrolled diffuse sources in SPZ**	yes or no	dependent on the stakeholder compliance and designation status of the legislation.	catchment management variables prior to the WFD implementation
BN 05	Mediating	Chance	Discrete	Labelled	**uncontrolled point sources in SPZ**	yes or no	dependent on the stakeholder compliance and designation status of the legislation.	catchment management variables prior to the WFD implementation
BN 06	Mediating	chance	discrete	labelled	**existing risk of GW pollution**	high, low	yes - is based on both the presence of a point or diffuse source within the source protection zone, and the susceptibility of the GW to contamination. No - is based on no risks identified in source protection zone, and reduced susceptibility of the GW to contamination.	catchment management variables prior to the WFD implementation
BN 07	Background	Chance	Discrete	Labelled	**AW Catchment Management in AMP 5**	Implemented/ not implemented	specified in AMP for implementation or not. (assumed to include elements of data sharing, stakeholder education and awareness raising, and development of stakeholder relationships)	Variables in the first RBMP implementation
BN 08	Mediating	Chance	Discrete	Labelled	**stakeholder NVZ compliance RBMP 1**	compliant or non-compliant	Stakeholders complying with NVZ or not, through observation of activities or self-assessment.	Variables in the first RBMP implementation

BN ref number	**BN variable type**	**BN variable category**	**BN variable kind**	**BN variable subtype**	**Abbreviated name for variable in Bayesian network**	**Name the state/s to be used in the model**	**Definition of states**	**location in the network**
BN 09	Mediating	Chance	Discrete	Labelled	**stakeholder WFD measures compliance in RBMP 1**	compliant or non-compliant	Stakeholders complying with WFD measures or not, through observation of activities or self-assessment.	Variables in the first RBMP implementation
BN 10	Mediating	Chance	Discrete	Labelled	**NVZ designation RBMP 1**	designated, not designated	dependent on stakeholder compliance and designation status of NVZ	Variables in the first RBMP implementation
BN 11	Mediating	Chance	Discrete	Labelled	**Effectiveness of NVZ RBMP 1**	Effective, not effective, No NVZ	dependent on stakeholder compliance and designation status of NVZ	Variables in the first RBMP implementation
BN 12	Mediating	Chance	Discrete	Labelled	**uncontrolled point sources in SPZ RBMP 1**	yes or no	dependent on the stakeholder compliance and designation status of the legislation.	Variables in the first RBMP implementation
BN 13	Mediating	chance	discrete	labelled	**risk of GW pollution 2010-15**	high, low	yes - is based on both the presence of a point or diffuse source within the source protection zone, and the susceptibility of the GW to contamination. No - is based on no risks identified in source protection zone, and reduced susceptibility of the GW to contamination.	Variables in the first RBMP implementation
BN 14	Mediating	Chance	Discrete	Labelled	**uncontrolled diffuse sources in SPZ RBMP 1**	yes or no	dependent on the stakeholder compliance and designation status of the legislation.	Variables in the first RBMP implementation
BN 15	mediating	Chance	Discrete	Labelled	**effectiveness of protection measures RBMP 1**	effective, not effective, no measure	effective is through the compliance of the stakeholder with the legislation requirements	Variables in the first RBMP implementation
BN 16	Background	Chance	Discrete	Labelled	**DrWPA in RBMP 1**	designated or not designated	specified within the RBMP	Variables in the first RBMP implementation
BN 16	Background	Chance	Discrete	Labelled	**DrWPA in RBMP 1**	designated or not designated	specified within the RBMP	Variables in the first RBMP implementation
BN 16	Background	Chance	Discrete	Labelled	**DrWPA in RBMP 1**	designated or not designated	specified within the RBMP	Variables in the first RBMP implementation

BN ref number	**BN variable type**	**BN variable category**	**BN variable kind**	**BN variable subtype**	**Abbreviated name for variable in Bayesian network**	**Name the state/s to be used in the model**	**Definition of states**	**location in the network**
BN 17	Background	Chance	Discrete	Labelled	**Safeguard zone RBMP 1**	designated / not designated	Stipulated in the RBMP PoMs	Variables in the first RBMP implementation
BN 18	Background	Chance	Discrete	Labelled	**WPZ in RBMP 1**	yes, no	Stipulated in the RBMP PoMs	Variables in the first RBMP implementation
BN 19	Mediating	chance	discrete	labelled	**GW at risk of failure of WFD objectives by 2015.**	high, low	yes - is based on both the presence of a point or diffuse source within the source protection zone, and the susceptibility of the GW to contamination. No - is based on no risks identified in source protection zone, and reduced susceptibility of the GW to contamination.	Variables in the first RBMP implementation
BN 19	Mediating	Chance	Discrete	Labelled	**GW at risk of failure of WFD objectives by 2015.**	High or low	dependent on the state of the current trend of water quality, existing water quality, and the existing risk of contamination.	Variables in the first RBMP implementation
BN 20	Background	Chance	Discrete	Labelled	**Soil permeability**	high permeability or low permeability	nature of permeability determined by the Hydrology of Soil type classification system (Boorman, et al , 1995)	Physical environment variables
BN 20	Background	Chance	Discrete	Labelled	**Soil permeability**	High permeability, low permeability	based on HoST classification.	Physical environment variables
BN 21	Background	chance	discrete	labelled	**Geology type**	chalk, other	yes - is based on the potential exposure of the GW to point and diffuse sources of pollution, and assumed indicative relationship with the nature of the geology, and depth to the aquifer. No - is based on no risk being present, due to no pollution sources present, and poorly draining geology and potential deep aquifer.	Physical environment variables

BN ref number	**BN variable type**	**BN variable category**	**BN variable kind**	**BN variable subtype**	**Abbreviated name for variable in Bayesian network**	**Name the state/s to be used in the model**	**Definition of states**	**location in the network**
BN 22	Background	Chance	Discrete	Labelled	**Depth of unsaturated zone**	shallow or deep	Shallow is determined based on < than or equal to 20 meters below datum point (mbdp) (in this case it is ground level). Deep is determined as > 20 mbdp.	Physical environment variables
BN 23	Background	chance	discrete	labelled	**GW vulnerability to contamination**	yes or no	yes - is based on the potential exposure of the GW to point and diffuse sources of pollution, and assumed indicative relationship with the nature of the geology, and depth to the aquifer. No - is based on no risk being present, due to no pollution sources present, and poorly draining geology and potential deep aquifer.	Physical environment variables
BN 24	Background	Chance	Discrete	Labelled	**Current trend of GW quality**	upward, stable, decreasing	annual change indicating the trend.	Physical environment variables
BN 25	background	Chance	Discrete	Labelled	**Current raw water quality**	<45 mg/l, > 45 mg/l	> 45 mg/l of nitrate present in raw water. > 45 mg/l of nitrate present in the raw water for an annual average.	Physical environment variables
BN 26	background	Chance	Discrete	Labelled	**blending used**	yes or no	yes = blending is used, no = not used.	management of potable water supply
BN 27	background	Chance	Discrete	Labelled	**Alternative sources**	yes or no	yes = available, no = unavailable	management of potable water supply
BN 28	background	Chance	Discrete	Labelled	**nitrate concentration of alternative source**	< 45 mg/l, > 45 mg/l	> 45 mg/l of nitrate present in raw water. > 45 mg/l of nitrate present in the raw water for an annual average.	management of potable water supply
BN 28	Background	chance	discrete	labelled	**nitrate concentration of alternative source**	< 45 mg/l, > 45 mg/l	Identification of the implications of the pass or fail of the DWD standards, which would inform the likelihood of interruptions to supply, and the need for further investment in treatment.	management of potable water supply

BN ref number	**BN variable type**	**BN variable category**	**BN variable kind**	**BN variable subtype**	**Abbreviated name for variable in Bayesian network**	**Name the state/s to be used in the model**	**Definition of states**	**location in the network**
BN 29	Background	chance	discrete	labelled	**blended water quality**	< 45 mg/l, > 45 mg/l	Identification of the implications of the pass or fail of the DWD standards, which would inform the likelihood of interruptions to supply, and the need for further investment in treatment.	management of potable water supply
BN 30	Background	Chance	Discrete	Labelled	**Ion exchange used**	yes or no	present or absent at site. (in addition to blending dependent on additional source water quality)	management of potable water supply
BN 31	Background	chance	discrete	labelled	**processed water quality in AMP 5**	< 45 mg/l, > 45 mg/l	Identification of the implications of the pass or fail of the DWD standards, which would inform the likelihood of interruptions to supply, and the need for further investment in treatment.	management of potable water supply
BN 32	Background	chance	discrete	labelled	**Potable water standards**	< 45 mg/l, > 45 mg/l	Identification of the implications of the pass or fail of the DWD standards, which would inform the likelihood of interruptions to supply, and the need for further investment in treatment.	management of potable water supply
BN 33	background	Chance	Discrete	Labelled	**Trend in GW quality in 2015**	upward, stable, rising	Using regression analysis of historical monitoring data for a site, Upward trend is based on the evidence of a positive	Future groundwater quality and trend
BN 34	background	Chance	Discrete	Labelled	**GW quality in 2015**	upward, stable, decreasing	> 45 mg/l of nitrate present in raw water. > 45 mg/l of nitrate present in the raw water for an annual average.	Future groundwater quality and trend
BN 34	Mediating	chance	discrete	labelled	**GW quality in 2015**	upward, stable, decreasing	yes - is based on both the presence of a point or diffuse source within the source protection zone, and the susceptibility of the GW to contamination. No - is based on no risks identified in source protection zone, and reduced susceptibility of the GW to contamination.	Future groundwater quality and trend

End of Appendix